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RADIATION HAZARDS

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on

Radiation Hazards

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AGARD Lecture Series No.78

RADIATION HAZARDS

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PREFACE

This Lecture Series No.78, on the subject of Radiation Hazards, is sponsored by the Aerospace Medical Panel of AGARD, and is implemented by the Consultant and Exchange Programme.

During the last 25 years there has been a remarkable development and increase in the number of processes and devices that utilise or emit non-ionizing radiation which includes ultra-violet, visible light, infrared, microwave, radiofrequency, ultrasound. Such devices are used in all sectors of our society for military and industrial, telecommunications, medical and consumer applications. Although there is information on biological effects and potential hazards to man from exposure to these energies, considerable confusion and misinformation has permeated not only the public press but also some scientific and technical publications. Much of the confusion stems from misunderstanding of the fundamentals of energy-tissue interaction, threshold phenomena, personnel exposure and product emission standards, such as those promulgated in the United States and adopted by the Western Countries and Japan in contrast to the personnel exposure criteria of Eastern European Countries. This series of Lectures by experts in the field provides a scientifically accurate, authoritative review and critical analysis of the available information and concepts to give a basis for informed judgements and judicious application of these energies for maximal benefit and minimum risk or hazard to man.

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Biologic and Pathophysiologic Effects of Exposure to Microwave or Ultrasonic Energy - An Overview

by

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During the last 30 years, there has been a remarkable development and increase in the number of processes and devices that utilize or emit non-ionizing radiant energies such as microwaves, a form of electromagnetic wave energy and ultrasound representative of mechanical vibration. These energies are used in all sectors of our society for military, industrial, telecommunications, medical, and consumer applications. More recently, the use of ultrasound in biology and medicine has been considerably expanded. These increases in sources of non-ionizing radiant energy have resulted in growing interest on the part of government regulatory agencies, industrial and military physicians, research workers, clinicians, and even environmentalists. Although there is information on biologic effects and potential hazards to man from exposure to microwaves or ultrasound, considerable confusion and misinformation has permeated not only the public press but also some scientific and technical publications.

Interest in the biologic effects of high frequency currents goes back to the work of D'Arsonval i 1893 (1) who reported physiologic effects from a device capable of delivering a frequency of several hundred thousand oscillations per second. This was followed by the introduction of "ultrashortwave" therapy in the early part of the twentieth century (2). Before World War II, the development and therapeutic applications of radiofrequency energy were further stimulated by the work of Schliephake (3). Rajewsky, Schaefer, Schwan, and associates which is described in the publications by Rajewsky (4), Liebesny (5), Pätzold (6), and Malov (7). To obtain an appreciation of the fundamental work that was going on during this period, review of these publications is especially useful.

During the latter part of World War II, the U.S. military services became interested in the possible hazards to personnel working around microwave sources, and the Office of Naval Research of the U.S. Navy began to sponsor research on the biologic effects of microwaves in 1948. In 1956, the U.S. Department of Defense assigned the responsibility for tri-service coordination of studies related to the biologic effects and potential hazards of microwave exposure to the U.S. Air Force. These studies contributed greatly to a better understanding of the biologic effects of microwaves. Findings of the tri-service program have been reviewed (8).

In 1968, the U.S. Bureau of Radiological Health sponsored a symposium on the Biological Effects and Health Implications of Microwave Radiation in Richmond, Virginia. This Symposium was held to provide an indication of the state of knowledge in the area of microwave health effects at that time. Subsequently, several symposia have been held both in the U.S. and the USSR on the general topic of the biological effect of microwaves.

In October, 1973, the first truly international Symposium on Biologic Effects and Health Hazards of Microwave Radiation was held in Warsaw, Poland under the sponsorship of the World Health Organization, U.S. Department of Health, Education and Welfare, and the Scientific Council to the Minister of Health and Social Welfare, Polish Peoples' Republic.

Ultrasound has not been studied as a naturally occurring phenomenon except for low-frequency, low-intensity emanations of animal origin (9). The noise spectra of jet propulsion devices contain a broad range of ultrasonic frequencies which were initially believed to be the basis for the headaches, nausea, undue fatigue, dizziness, and other complaints reported by personnel who worked in the jet sound field. Subsequent research, however, indicated no support for this belief. It was suggested that the ill effects were more probably due to the tremendous intensities of sound, over 140 db, created in the audible range of frequencies by the jet engine (10). Interest in the possible harmful effects of ultrasound on man became highlighted when ultrasonic devices came into more general use.

To provide a perspective on the uses of microwaves in the civilian sector in the U.S., Villforth (11) has noted: about 425,000 microwave ovens were in use, mostly civilian, in 1972. An estimated 15,000 shortwave and 15,000 microwave diathermy devices were in use, mostly civilian, in 1972. Approximately 120,000 microwave communications towers, each with several separate sources, were in use at the end of 1972, approximately 75% civilian. About 2 million people are treated annually with radiofrequency (microwave) diathermy. An additional 60,000 people may be occupationally exposed in practitioner's offices and clinics. A significant portion of the total U.S. population of 200 million is exposed in varying degrees to microwaves from communications devices; some individuals are continually exposed. Occupational exposure to radar exists in the Armed Forces, FAA, civilian airlines, shipping, and other industries. The number of microwave devices projected for use in 1980 include: ovens, 5,000,000; diathermy, no estimate with any degree of accuracy; for communications, 250,000 towers will have been constructed by 1976.

In regard to ultrasonic devices, Villforth (11) has reported that there are an estimated 50,000 cleaning units now in use in the U.S. These are used in a variety of industries and other non-home applications. Approximately 50,000 other commercial/industrial applications were in use at the end of 1972, largely civilian. In 1970, there were approximately 3,000 medical diagnostic devices in use; however, the use-growth pattern suggests this may have increased to nearly 10,000 in 1972, mostly in the civilian area. Industry sales projections and surveys indicate that about 33,000 diathermy units existed at the end of 1972, largely civilian. The very rapid increases in sales of diagnostic ultrasonic devices indicate that approximately 175,000 may be in use by 1976. Population at risk is not known with any degree of accuracy. Based on extrapolations of a 1970 equipment survey, an estimated two million people are treated annually with ultrasonic diathermy. Mixer and other industrial commercial applications accounted for approximately 50,000 units in use by the end of 1972. The number of ultrasonic devices projected for use in 1980 include: cleaning equipment, 200,000 units; medical diagnostic, approximately 175,000; diathermy, 100,000; commercial/industrial, 180,000.

Although thermal effects of microwave absorption have been well demonstrated and documented, some investigators suggest non-thermal or specific effects due to microwave exposure. When animals or man are exposed to microwaves, the absorbed energy is converted to heat which, if of sufficient degree, may induce physiologic responses as a reaction to the increased body temperature or subtle alterations in thermal

gradients in the body. Although there have been reports of functional changes of the neuroendocrine, cardiovascular, or central nervous system as a result of microwave exposure, these responses are consistent with the pattern of physiologic adjustment to thermal inputs into the body.

Of interest in this context is a conclusion formulated at the International Symposium on Biologic Effects and Health Hazards of Microwave Radiation, Warsaw, 1973. Microwave biologic effects may be divided into three categories: high average intensities (>10 mW/cm^2) at which distinct thermal effects occur which in some instances may be hazardous; the range below 1 mW/cm^2 in which gross thermal effects are improbable; the range of intermediate or subtle effects from about 1-10 mW/cm^2 in which weak thermal but noticeable effects occur as well as direct field effects and perhaps other effects of a microscopic or macroscopic nature the details of which are at present unclarified. The border limits of these regions are approximate and may differ for various species of animals and may also depend on a variety of parameters such as frequency and modulation.

The interactions of ultrasound in tissue have been studied, however, these interactions are quite complex, and much further study is needed to understand completely the interactions of ultrasound. Presently, much of the reported effects of ultrasound may be explained in light of existing theory. When ultrasound is absorbed by tissue, heat is produced. In addition, ultrasound produces biological effects that cannot be explained on the basis of heating alone.

In June 1972, the <u>New England Journal of Medicine</u> published an editorial entitled "Application of Ultrasound in Medicine" (12). The editorial made reference to the unquestioned value of ultrasound as a diagnostic tool and that its use in clinical medicine was such that it "can be considered essential to good patient care." It then continued: "The mechanisms of interactions between tissues and ultrasound are not as yet completely known, and although ultrasonic irradiation of biological materials in vitro under specific experimental conditions has been reported to cause chromosomal aberrations, from all the evidence available, both experimental and clinical, it is conceded that the current diagnostic practice pose no short-term or long-term hazard to the patient or to the fetus subjected to whole-body irradiation." "In addition to its relative safety as compared to ionizing radiation, ultrasound used as Sonar (or in pulse-echo mode) can often yield information on the presence and location of interfaces between and within soft tissues unobtainable by X-rays or any other means." On the other hand, a recent reviewer of the subject of biologic effects of ultrasound (13) has observed: "...the belief that diagnostic ultrasound is safe seems to be based on the low power density and the fact that physicians have not recognized adverse effects in clinical use. There is the apparent comfort that no adverse effects have been shown in the laboratory at diagnostic levels. Yet, subtle effects in humans have not been looked for adequately and possibly even all gross effects have not been monitored sufficiently. It is even doubtful that the entire spectrum of potentially harmful effects of ultrasound on animals has been studied adequately." It should be pointed out that similar criticism has been leveled at microwave bioeffects studies and reports.

Because of the complexity of the interactions of nonionizing radiation in biological systems, an interdisciplinary approach is necessary to assess and elucidate the problems that evolve as this field advances and as the use of these energies expands. It is important to maintain a proper perspective and assess realistically the biomedical effects of these radiant energies so that the worker or general public will not be unduly exposed nor will research, development and beneficial utilization of these energies be hampered or restricted by an undue concern for effects which may be non-existent or minimal in comparison to other environmental hazards. The goal of this lecture series is to review and place the available information and concepts in proper perspective to understand and encourage the full potential for the beneficial use of these radiant energies, at the same time preventing adverse effects to individuals exposed to these energies.

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Pathophysiologic Aspects of Exposure to Microwaves

by

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INTRODUCTION

For the purposes of these lectures, microwaves will be defined as that portion of the electromagnetic radiant energy spectrum which encompasses the frequency range of 300 MHz - 300 GHz with wavelengths in free space of 1 meter to 1 millimeter. Extensive investigations into microwave bioeffects during the last quarter century show conclusively that, for frequencies between 1200 and 24,500 MHz, exposure to power density of 100 mW/cm² for 1 h or more could have pathophysiologic manifestations of a thermal nature. Such manifestations would be characterized by temperature rise, which is a function of the thermal regulatory processes, and active adaptation of the animal. The end result is either reversible or irreversible change, depending on the conditions of the irradiation and the physiologic state of the animal. At power densities below 100 mW/cm², however, evidence of pathologic changes is nonexistent or equivocal. A great deal of discussion, nevertheless, has been engendered concerning the relative importance of thermal or nonthermal effects of radiofrequency (RF) and microwave radiation.

The results of some in vitro studies have been considered as evidence of nonthermal effects of RF radiation. Although some investigators and reviewers still question the interpretation of these so-called nonthermal effects (1-6), several support nonthermal interactions between tissues and electric and magnetic fields (7-11).

THERMAL EFFECTS

Body temperature increase during exposure to microwaves depends on: a) the specific area of the body exposed and the efficiency of heat elimination; b) intensity of field strength; c) duration of exposure; d) specific frequency or wavelength; and e) thickness of skin and subcutaneous tissue. These variables determine the percentage of radiant energy absorbed by various tissues of the body (12, 13).

In partial body exposure under normal conditions, the body acts as a cooling reservoir, which stabilizes the temperature of the exposed part. The stabilization is due to an equilibrium established between the energy absorbed by the exposed part of the body and the amount of heat carried away from it. This heat transport is due to increased blood flow to cooler parts of the body, maintained at normal temperature by heat-regulating mechanisms such as heat loss due to sweat evaporation, radiation, and convection. If the amount of absorbed energy exceeds the optimal amount of heat energy that can be handled by the mechanisms of temperature regulation, the excess energy will cause continuous temperature rise with time. Hyperthermia and, under some circumstances, local tissue destruction can result (12, 13).

THRESHOLD FOR PERCEPTION

Awareness of microwave exposure is developed by several mechanisms including cutaneous thermal sensation or pain. The physiology of thermal sensation and pain, which is essentially the basis for cutaneous perception of microwave energy, has been the subject of several studies. These studies suggest that a threshold sensation is obtained when the temperature of the warmth receptors is increased by a certain amount ΔT.

Schwan et al (14) found that if a person's forehead is exposed to 74 mW/cm² of 3000 MHz microwaves, the reaction time (the time which elapses before the person is aware of the sensation of warmth) varied between 15 and 73 seconds. Warmth perception of 56 mW/cm² ranged between 50 seconds and 3 minutes of exposure. Hendler and associates (15, 16) made detailed studies of the cutaneous receptor response of man to 10,000 MHz and 3000 MHz microwaves and for infrared (Table 1). For a 4 second exposure to 10,000 MHz over a 37 cm² area of the forehead, the threshold for thermal sensation is 12.6 mW/cm² and 25 mW/cm² for exposures lasting 0.5 second. For the entire face, assuming uniform temperature sensitivity of the facial skin, the thermal sensation threshold would be 4-6 mW/cm² for a 5-second exposure or approximately 10 mW/cm² for a 0.5-second exposure.

TABLE 1

Stimulus Intensity and Temperature Increase to Produce a Threshold Warmth Sensation*

	3000 MHz	10,000 MHz		Far Infrared	
Exposure Time (sec)	Power Density (mW/cm²)	Power Density (mW/cm²)	Increase in Skin Temp. (°C)	Power Density (mW/cm²)	Increase in Skin Temp. (°C)
1	58.6	21.0	.025	4.2 - 8.4	.035
2	46.0	16.7	.040	4.2	.025
4	33.5	12.6	.060	4.2	---

*37 cm² forehead surface area - data from Hendler et al (15, 16).

Cook (17) investigated the pain threshold for 3000 MHz microwaves. As far as could be judged, the sensations of warmth and pain with microwave heating differed little from those felt when heating was produced by infrared radiation. Apparently a thermal pain sensation is evoked when end-organs located approximately 1.5 mm below the skin surface reach a temperature of about 46°C. Power density levels for pain threshold

[illegible] exposed area of 9.5 cm² were 1.1 W/cm² for a 20 second exposure to 830 mW/cm² for exposures [illegible] minutes. The thresholds for pain sensation as a function of exposure time is shown in Table 11. The pain threshold was lower (560 mW/cm²) for an exposed area of 53 cm² in contrast to [illegible] for a 9.5 cm² area.

TABLE 11

Threshold for Pain Sensation as a Function of Exposure Duration
(3000 MHz, 9.5 cm² area)

Power Density (W/cm²)	Exposure Time (sec)
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]

[illegible]

These studies [illegible] microwaves induced thermal sensation and pain suggest that for levels considered to [illegible] thermal sensation [illegible] serve as a warning mechanism against undue exposure. [illegible] required for injury.

[illegible]

Cataracts have been produced [illegible] experimental animals, [illegible] rabbits, when the eyes were [illegible] exposed [illegible] power densities of microwaves [illegible] periods ranging from several minutes to hours. [illegible] reports of microwave induced cataracts [illegible] have been disputed. The subject of microwaves and cataracts [illegible] will be presented separately.

[illegible]

The effect of microwaves [illegible] the testes has been studied (18-21). Exposure of the scrotal area at high power densities [illegible] resulted in various degrees of testicular damage such as edema, enlargement of the testis, atrophy, fibrosis, and coagulation necrosis of seminiferous tubules in rats, rabbits, or dogs exposed [illegible] 24,000 MHz. Whole-body exposure of dogs to 24,000 MHz, 20 mW/cm², several hours a day [illegible] affect reproduction. Exposure to 3000 MHz, 8 mW/cm² [illegible] affect [illegible] rats [illegible].

Although studies indicate that high power density exposure can affect the testes and ovary, these responses can be related to the heating of the organs. There are other reports, however, that [illegible] exposure can result in impairment of spermatogenesis and reproductive function without measurable temperature increase of the testes (24, 25).

Reports of sterility or infertility in the human from exposure to microwaves are questionable. Barron and associates (26, 27) found no evidence of fertility changes in their human surveys. There is one case report of altered fertility in a man from unusually large exposures to microwaves (28). In this report, radar has been implicated as being responsible for oligospermia and infertility in a young man previously demonstrated to be fecund. The difficulty in evaluating this report is that there was no preexposure examination of this individual, so any causal relationship is very tenuous. The authors note that the patient frequently performed maintenance on the radar antenna while the equipment was in operation; did not wear protective clothing, and was exposed repeatedly to microwave power densities more than 3000 times the currently accepted safe level established by the U.S. Air Force.

CHROMOSOME CHANGES

Some investigators have reported chromosome changes in various plant and animal cells and tissue cultures (29-33). These studies have been criticized by those who feel that the systems were subjected to a thermal stress; the chosen parameters of the applied field caused biologically significant field induced force effects and these experiments have not yet been independently replicated (34, 35). There is thus no direct or confirmed evidence of genetic effects due to exposure to RF or microwaves.

Sigler et al (36) reported that there was a higher incidence of children with Down's syndrome among fathers with prior occupational exposure to radar. This epidemiological study of Down's syndrome was initiated primarily to determine whether there was a relationship between parental exposure to ionizing radiation and the occurrence of this syndrome among offspring. The principal stimuli for this study were the relationship between known and recorded exposure to ionizing radiation and chromosomal aberrations, the association of leukemia and mongolism and the leukemogenic effect of ionizing radiation. In addition to collecting data for this major objective, information was obtained and analyzed concerning other factors, such as parental age and maternal reproductive patterns, which might be associated with chromosomal aberrations (37).

In contrast to the mothers, the fathers of the children with Down's syndrome did not have significantly greater exposure to ionizing radiation than did the control fathers. No differences were found in the occupations of the fathers of Down's syndrome children and the controls, except for a higher frequency of military service for the fathers of the Down's syndrome children - 63.1% as compared with 56.6% for control fathers. In addition, a history of radar exposure was obtained from fathers, which indicated that 8.7% of the fathers of the children with Down's syndrome and 3.3% of the control fathers had had contact with radar, both in and outside of the armed forces -- a difference which is of borderline statistical significance (P<.02) (37).

It should be noted that the authors themselves only suggested the relationship between Down's syndrome and paternal radar exposure. The radiation history of the fathers provided a contrast to that of the mothers.

There was a marked similarity in the history of radiation exposure reported by the fathers of Down's syndrome children and of the controls, except for the suggested relationship between Down's syndrome and paternal radar exposure. With the small numbers available, it is most likely this finding is a chance observation. In addition, one has to recognize the possibility of inadvertent unknown and/or unrecorded exposure to ionizing radiation or other genetic perturbing agent. This is an ever-present caution in retrospective epidemiologic surveys.

HEMATOPOIESIS

Although a number of investigators state that the blood and blood forming system are not affected by acute or chronic microwave exposure (27, 38-40), effects on hematopoiesis have been reported (41-48). The time of onset and degree of hematopoietic change may be dependent on the wavelength, field intensity and duration of exposure (45-46). It is suggested that leukocyte response is related to hypothalamic-hypophysial-adrenal stimulation due to thermal stress (49).

Hyde and Friedman (50) studied the effects in mice from exposure to 3000 MHz, 20 mW/cm² and 10,000 MHz, 17, 40, or 60 mW/cm² up to 15 minutes. No significant effect on total or differential leukocyte count or hemoglobin concentration was noted immediately, 3, 7, or 20 days after exposure. There were no changes in femoral bone marrow other than an inconstant slight increase in the eosinophil series of the exposed animals which was not reflected in peripheral blood counts.

Kitsovskaya (46) subjected rats to 3000 MHz according to the following schedule: 10 mW/cm², 60 min, 16 days; 40 mW/cm², 15 min, 20 days; 100 mW/cm², 5 min, 6 days. At 40 mW/cm² and 100 mW/cm², total RBC, WBC, and absolute lymphocytes were decreased; granulocytes and reticulocytes were elevated. At 10 mW/cm², total WBC and absolute lymphocytes decreased, and granulocytes increased. Bone marrow examination revealed erythroid hyperplasia at the higher power levels. The blood did not return to its normal state months after the series of irradiations was discontinued.

Baranski (48, 51) exposed guinea pigs and rabbits to 3000 MHz pulsed or CW 3.5 mW/cm² power density for 3 months, 3 hrs daily. Peripheral blood, bone marrow, lymph nodes and spleen were examined. Increases in absolute lymphocyte counts in peripheral blood, abnormalities in nuclear structure and mitosis in the erythroblastic cell series in the bone marrow and in lymphoid cells in lymph nodes and spleen were observed. No alteration in the granulocyte series was noted. Baranski suggests that extrathermal complex interactions seem to be the underlying mechanism for the changes.

Budd et al (52) investigated the sensitivity of the fetal rat hematological system following in utero microwave irradiation. Pregnant Sprague-Dawley rats were exposed one at a time to whole-body 2450 MHz 100 mW/cm² CW microwaves at 15 days gestation. Under these conditions the rectal temperature of the pregnant rats increased 4.2°C above that of the controls. Hematological changes were measured in the pregnant rats at 4 hours, 24 hours, and 5 days post-irradiation (shortly before the fetuses were removed). Body and spleen weights and hematological changes were measured in the fetal rats at 20 days gestation. No significant differences were found between the control and microwave exposed pregnant rats in body weight, total leukocyte count, erythrocyte count, hematocrit, or hemoglobin value. Microwave irradiated fetuses had significantly lower spleen weights ($P<0.05$), total leukocyte counts ($P<0.01$), and somewhat lower hemoglobin values ($P<0.10$) than controls. No appreciable differences were observed between microwave irradiated fetuses and their controls in body weight, ^{59}Fe uptake in blood or fetal resorption. The lack of any effect in the pregnant rat exposed to 100 mW/cm² or any greater effect in the foetus than that reported is noteworthy.

Spalding (53) exposed mice to 800 MHz two hours daily for 120 days in a closed system (wave guide) at an incidence level of 43 mW/cm². Body weight, red and white blood cell count, hematocrit, hemoglobin, growth, voluntary activity and life span remained normal. Distinct changes in the proportions of white and red bone marrow stem cells have been observed in rabbits chronically exposed to meter waves at 1 mW/cm² (54).

In dogs exposed whole-body to pulsed microwaves there was a marked decrease in lymphocytes and eosinophils after six hours, 2800 MHz 100 mW/cm² (55). The neutrophils remained slightly increased at 24 hours, while eosinophil and lymphocyte values returned to normal levels. Following two hours of exposure at 165 mW/cm², there was a slight leukopenia and decrease in neutrophils. When the exposure was of three hours duration, leukocytosis was evident immediately after exposure and was more marked at 24 hours, reflecting the neutrophil response. There was a moderate decline in lymphocytes immediately following two to three hours of exposure, with recovery to the pre-exposure level at 24 hours. Eosinophil change was negligible at the termination of three hours exposure and moderately decreased at 24 hours.

After exposure to 1285 MHz, 100 mW/cm² for six hours, there was an increase in leukocytes and neutrophils. At 24 hours, the neutrophil level was still noticeably increased from the pre-exposure level. Lymphocyte and eosinophil values were moderately depressed and at 24 hours slightly exceeded their initial value.

Six hours of exposure to 200 MHz (CW) 165 mW/cm² resulted in a marked increase in neutrophils and a mild decrease in lymphocytes. The leukocyte count was further increased, and the lymphocytes markedly increased the following day. Eosinophils were moderately decreased (55).

Exposure of mice to 2450 MHz, 100 mW/cm² for 5 minutes resulted in a decrease followed by an increase in Fe^{59} uptake in the spleen and bone marrow (56). Alteration in ferro-kinetics was also found in rabbits and guinea pigs exposed to 3000 MHz at 1 mW/cm² or 3 mW/cm², 2-4 hours daily, 14-79 days (57).

Early and sustained leukocytosis in animals exposed to thermogenic levels of microwaves may be related to stimulation of the hematopoietic system, leukocytic mobilization, or recirculation of sequestered cells. Eosinopenia and transient lymphocytopenia with rebound or overcompensation when accompanied by neutrophilia may indicate increased adrenal function.

Barron et al (26) reported an apparent decrease in polymorphonuclear cells and increase in eosinophils and monocytes in a group of radar workers. In a later report, however, the same authors (27) found these decreases to be incorrect due to a variation in a laboratory technician's interpretation.

Baranski and Czerski (47) reported on the hematologic examination of a large group of people occupationally exposed to microwaves. They concluded that a small drop in the number of erythrocytes takes place in all people exposed to microwaves; incidence is related to the length of employment with normalization later, a symptom which does not appear in groups having worked for one to five years. A tendency toward lymphocytosis with accompanying eosinophilia is apparent in persons having worked more than five years under conditions of low and medium microwave exposure. Three groups of leukocyte changes occur in persons exposed to substantial irradiation for more than five years: most frequent are absolute and relative

lymphocytosis: next in order is absolute lymphocytosis with monocytosis; and neutrophilic leukocytosis is last. About 50% of persons exposed to microwaves show a moderate drop in platelet number. This poses the question whether X-rays or other environmental factors may not be the entity or at least a contributor in such findings (58).

CARDIOVASCULAR EFFECTS

Several investigators report that exposure of animals or man to microwaves may result in direct or indirect effects on the cardiovascular system. Some authors suggest that exposure to microwaves at intensities that do not produce appreciable thermal effects may lead to functional changes that are observed with acute as well as chronic exposures. On the other hand, no serious cardiovascular disturbances have been noted in man or animals as a result of microwave exposure (59).

Increased heart rate has been observed in rabbits and dogs after exposure to power densities of 50-130 mW/cm^2 for variable periods of time ranging from 10-140 minutes (60, 61, 62). Slowing of the heart rate is reported by some investigators with low (or what they consider "nonthermal") levels of microwaves (39, 63), although others have reported increased heart rate with low-level microwave exposure over the dorsal aspect of rabbits (64, 65). Increase in blood pressure has been reported (60, 66, 67).

Homodynamic response of the dog exposed to thermogenic levels of 2800 MHz pulsed resembles that of acute heat stress as manifested by early hemodilution followed by hemoconcentration. As the exposure is prolonged, hemoconcentration becomes more evident. Dogs exposed at 165 mW/cm^2 show a body weight loss of 2.0%/hr. At 100 mW/cm^2, there is a weight loss of 1.25%/hr, and hemodilution occurs, as contrasted with hemoconcentration evident at 165 mW/cm^2 (55).

Subbota (67) has noted that in rabbits chronically exposed to 2450 MHz, 10 mW/cm^2, little change in arterial pressure was evident. However, hemodynamic shifts were quite clearly in evidence even at 1 mW/cm^2. No hemodynamic shifts were observed beginning with the 4th or 5th treatment. When the rabbits were exposed to 50 mW/cm^2, the arterial pressure dropped, then recovered to its initial level after 1-2 hours. Characteristically, these effects were registered only after the first few microwave treatments, and later, as the treatments were repeated (once every 1-3 days), the arterial pressure change became smaller in degree until disappearing the 9th or 10th treatment. The rectal temperature rise was 1-1.7°C after the first exposure, but 0.7-0.9°C after 9 to 10 treatments.

Presman and Levitina (64, 65) interpret their data as indicating an effect on the parasympathetic nervous system (vagus nerve) during ventral irradiation and on the sympathetic nervous system during dorsal exposure. Levitina (68) has suggested that the peripheral nervous system is the mediator between microwave radiation and its possible effects on heart rate.

McAfee (69) has pointed out how data can be misinterpreted to be the result of some unknown effect of microwave radiation, when hyperthermal effects are not involved. In cats, when peripheral nerves are stimulated by 45°C temperature, adrenal medullary secretion occurs and a rise in blood pressure is developed as a result of adrenal secretion (70). McAfee (71) questions whether experiments on the effect of microwave radiation on heart rate are carefully controlled for this possibility; if so, it is not mentioned in the literature.

Functional damage to the cardiovascular system indicated by hypotonus, bradycardia, delayed auricular and ventricular conductivity, decreased blood pressure, and decreased height of EKG waves in workers in RF or microwave fields has been reported (43, 72-75). Osipov (76), however, points out that these changes do not diminish work capacity, and are reversible. It has been reported that the functional state of the circulatory system of radar station operators who exercise regularly (preliminary gymnastics) is superior to that of persons who avoid physical exercise (77).

According to Sadchikova (78), two basic syndromes of hemodynamic disturbances induced by changes in regulatory reflex function exist, dependent on the preponderance of excitability of sympathetic or parasympathetic vegetative nervous centers. Clinical syndromes are induced simultaneously with or immediately after hazardous occupational exposure. Both types of reactions may be observed among persons exposed to microwaves at intensity levels of a few milliwatts/cm^2 for long periods of time. Neurocirculatory disturbances of a hypertensive character are related to the duration of exposure, vagotonic reactions occur during initial periods of work. Prolonged exposure induces progressive changes, interruption of exposure may induce a remission. Symptoms of sympathetic circulatory disturbances occur in persons exposed to low dose intensities of a few tens of microwatts/cm^2 with occasional exposures up to 1 mW/cm^2(78).

Tolgskaya and Gordon (79) observed morphological changes in receptors after one exposure to microwaves which decreased with repeated exposures. They suggest that receptors of the reflexogenic zone of the curve of the aorta, the carotid sinus, and all layers of the auricular wall are highly sensitive to microwaves.

It does appear that functional cardiac changes can occur as a result of microwave exposure which doubtless are due to response of the autonomic nervous system to thermal effects. It has been noted that thermal stimulation of peripheral nerves produces neurophysiological and behavioral changes (70). Interaction between the peripheral nervous system and the central nervous system could account for the reported effects on heart rhythm, blood chemistry, and ECG.

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PHYSICAL ASPECTS - ULTRASOUND

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Summary

Ultrasound, which is a form of energy consisting of mechanical vibrations the frequencies of which lie above the range of human hearing, travels through media in the form of waves. At frequencies of tens to hundreds of kilohertz, ultrasound may be generated and detected by magnetostriction; at higher frequencies, piezoelectric, and particularly ferroelectric, transducers are used. At megahertz frequencies, ultrasonic powers are most conveniently measured by radiation pressure detectors, or by calorimetry. In biological soft tissues, ultrasonic waves are usually in the longitudinal mode, and travel at velocities of around 1 500 m s^{-1}. The shape of ultrasonic field depends on the size of the transducer in relation to the wavelength. Focusing systems of quite small dimensions can be used to produce high intensities at megahertz frequencies. Specular reflection occurs at discontinuities in characteristic impedance which are large in relation to the wavelength; energy is scattered by smaller discontinuities within biological materials. In soft tissues, ultrasound is absorbed at a rate of about 1 dB cm^{-1} MHz^{-1} by broad-spectrum relaxation processes. The attenuation in both lung and bone, however, is very much higher, and their characteristic impedances differ greatly from those of soft tissues. The inclusion or occurrence of gas bubbles within liquids or soft tissues may have profound effects on the neighbouring ultrasonic field, due to phenomena broadly classified as cavitation effects.

Ultrasound is a form of energy which consists of mechanical vibrations the frequencies of which lie above the range of human hearing. The lower limit of the ultrasonic spectrum is generally taken to be about 20 kHz.

Ultrasonic vibrations travel through a medium in the form of a wave. The transducers used to generate and to detect ultrasonic waves are of various kinds, according to the frequencies, wave shapes and intensities which are involved.

At frequencies of tens to hundreds of kilohertz, the magnetostrictive transducer is appropriate. A magnetostrictive material has the property that the application of a magnetic field causes a change in physical dimensions, and vice versa. In the absence of an applied magnetic field, the magnetic domains of a magnetostrictive material are randomly orientated. The shape of each individual domain is asymmetrical. The application of an external magnetic field tends to rotate the domains into the same direction, and it is this change to a non-random orientation which causes the change to occur in the dimensions of the material. The change may be either positive or negative, and for a given field strength it is in the same direction irrespective of the sign of the applied field. Consequently, if an alternating magnetic field is applied - for example, by introducing the magnetostrictive material into the field of a solenoid carrying an alternating electric current - the magnetostrictor oscillates at twice the frequency of the magnetic field. Generally this difficulty can be overcome by the application of a non-varying magnetic field of a relatively large magnitude.

In any particular application, the choice of the magnetostrictive material depends upon several considerations, including the frequency and the intensity. At low frequencies and high intensities, nickel, and alloys of certain materials such as iron and cobalt, are appropriate, and generally a laminated construction is used to minimise eddy current losses. At high frequencies - in excess of about 50 kHz - and even at low frequencies at intensities below about 20 W cm^{-2} in water, synthetic ceramic materials known as ferrites have better characteristics than those of metals.

Certain materials have the property that the application of an electric field causes a change in physical dimensions, and vice versa. This is the piezoelectric effect, which occurs in some natural and synthetic crystals such as quartz and lithium sulphate. In addition, in some artificial ceramic materials, the individual change domains may be aligned in a manner analogous to the magnetic domains in a ferromagnetic material in a magnetic field. The analogy leads to the term "ferroelectric". Ferroelectric ceramics may be polarized during the manufacturing process, so that, unlike ferromagnetic transducers, an external polarizing field is unnecessary.

Probably lead zirconate titanate is the most widely used piezoelectric transducer at frequencies in the range 0.1 - 10 MHz. Its characteristics may be modified to control the frequency bandwidth. A great advantage of the piezoelectric ceramics is that they may be formed into any desired shape during manufacture, and polarized in any required direction. Although the most usual shape is that of a thickness-expanding disc, two other configurations are quite often used in ultrasonic applications. Firstly, spherical bowls are used, generally to produce focused ultrasonic fields. Secondly, cylinders with electrodes bonded onto their inner and outer curved surfaces are used as length expanders to drive various probes, and as omnidirectional receiving elements. Some typical arrangements are illustrated in Figure 1.

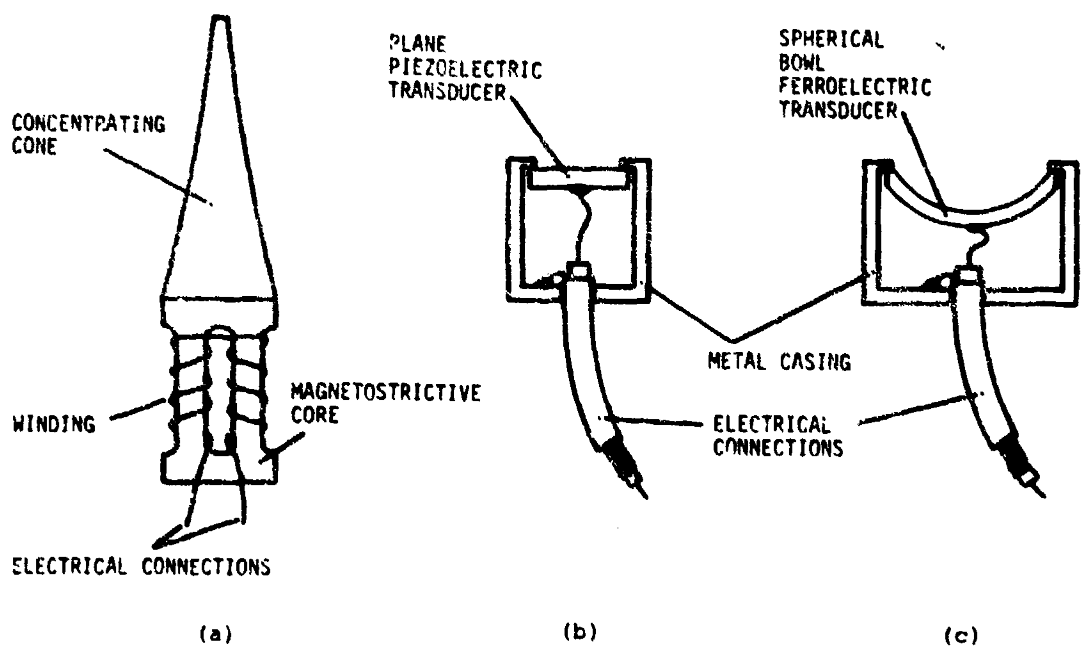

Fig. 1. Typical ultrasonic transducers and their mounting arrangements. (a) Magnetostrictive transducer with concentrating cone; (b) Piezoelectric disc transducer; (c) Ferroelectric spherical bowl transducer.

At megahertz frequencies, ultrasonic powers are most conveniently measured by radiation pressure detectors, or by calorimetry. A force becomes established across a region in which there is a change in the intensity of the wave. If the wave is completely absorbed, the force is equal to the incident power divided by the wave velocity. The theoretical basis of the effect is still somewhat controversial: but in practice, the simple relationship is that the absorption of an ultrasonic wave with a power of 1 W travelling in water produces a force equivalent to a weight of about 70 mg. Therefore, with a suitably designed "radiation pressure balance", measurements of force may be directly related to estimates of ultrasonic power. The construction of a typical radiation pressure balance is illustrated in Figure 2. In this instrument, the ultrasonic beam is arranged to be intercepted as it travels

through water by an absorber mounted on one end of a balance arm, thus producing a turning moment proportional to the ultrasonic power. This turning moment is balanced by a rider of known weight appropriately positioned on the other arm. Since it is not possible to find a material which does not reflect some of the incident energy - as explained later in this article - accurate instruments are arranged so that reflected energy does not introduce errors.

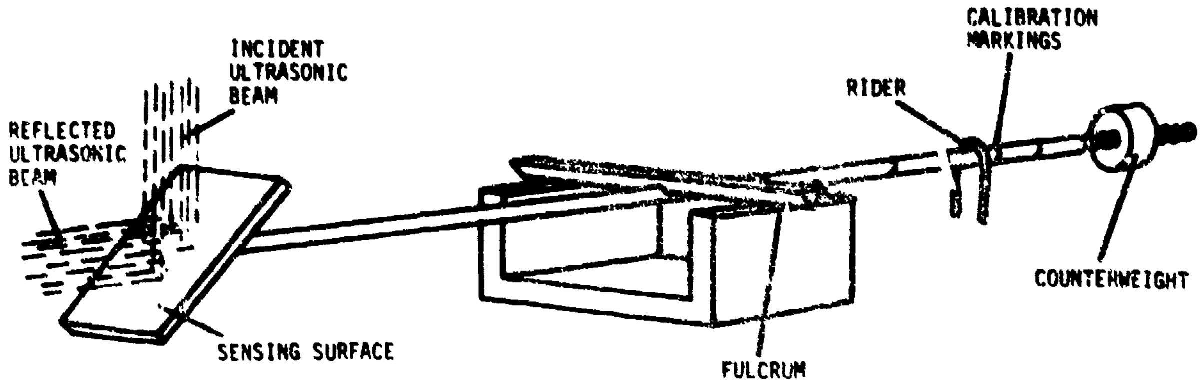

Fig. 2. Typical radiation pressure balance. The instrument operates under water. The ultrasound reflected from the partial absorber which forms the sensing surface at the end of the balance arm is travelling horizontally, and so does not produce an erroneous turning moment about the fulcrum.

This type of radiation pressure balance is suitable for the measurement of ultrasonic powers in the range 0.05 - 10 W. The measurement of power of less than 0.05 W requires a very sensitive system, since such small forces are involved. A convenient way around the difficulty is to use a modified analytical balance, which can typically measure a power of 2 mW (equivalent to a weight of 140 μg) with accuracy of 3%.

Calorimetry is a more fundamental but generally less convenient method of ultrasonic power measurement. It depends on the complete absorption of the ultrasonic energy within the body of a calorimeter, which allows the heat so produced to be measured. The method is tedious because of the necessity to wait whilst thermal equilibrum is achieved between measurements. It is relatively insensitive, because of the difficulty of measuring small amounts of heat. The principal source of error is due to the direct transfer of heat due to the inefficiency of the source, which is indistinguishable from that produced by the absorption of ultrasound. Despite the problems, instruments have been constructed in the laboratory which are capable of measuring powers in the range 0.1 - 10 W, and which agree quite closely with radiation pressure determinations.

In biological soft tissues, ultrasonic waves usually travel in the longitudinal mode. The particles of which the medium is composed vibrate backwards and forwards about their mean positions, so that energy is transferred through the medium in a direction parallel to that of the oscillations of the particles. The particles themselves do not move through the medium, but simply vibrate to and fro. The velocity at which the energy is propagated is determined by the delay which occurs between the movements of neighbouring particles. This depends on the elasticity and the density of the medium. In water, the velocity is 1 520 m s^{-1} at 37 °C. The values of the velocities in soft tissues are not precisely known, but range from about 1 450 m s^{-1} in fat to about 1 585 m s^{-1} in muscle.

The "ultrasonic field" of a transducer is the term used to describe the spatial distribution of its radiated energy. The analysis of the field is based on the application of Huygen's construction, in which the surface of the transducer is

considered to be an array of separate elements each radiating spherical waves in the forward direction. The elements move synchronously with equal amplitudes; thus, a disc is considered to be a piston the surface of which vibrates cophasally at constant amplitude. This is, however, a rather complicated situation for analysis, since three-dimensional geometry is involved. The theoretical distribution for such a source is shown diagrammatically in Figure 3.

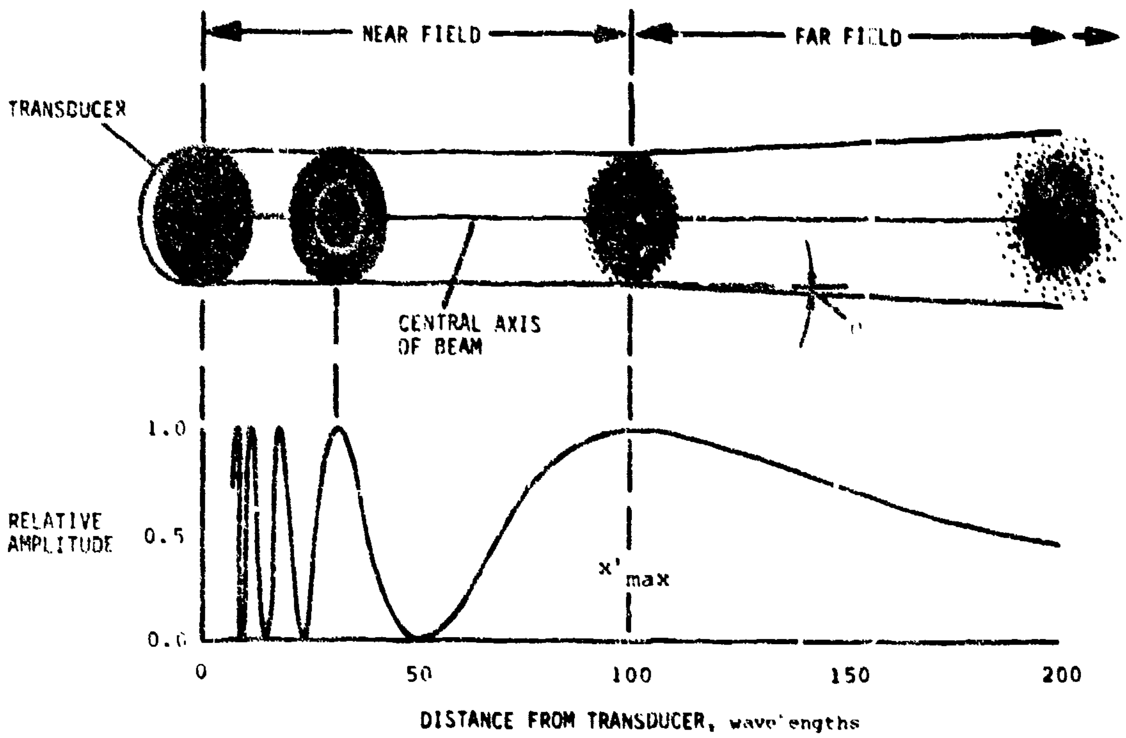

Fig. 3. Theoretical field distribution of a typical disc transducer. In this example, the transducer has a radius of 10 wavelengths. The ring diagrams represent the cross-sectional intensity distributions at selected positions along the central axis of the beam.

Moving along the central axis of the beam towards the source, the intensity increases until a maximum is reached at a distance x'_{max} from the source given by

$$x'_{max} = r^2/\lambda \qquad (1$$

where r is the radius of the source, λ is the wavelength of the ultrasound, and $r^2 >> \lambda^2$. The relationship between λ, the velocity c, and the frequency f, is that

$$\lambda = c/f \qquad (2$$

Increasingly closely spaced axial maxima and minima occur towards the source. At successive axial maxima and minima, starting at x'_{max} and moving towards the source, there are one, two, three, etc., principal maxima across the beam diameter. Thus, the beam has two distinct regions. The region between the source and x'_{max} is known as the "near field", and the beam is roughly cylindrical. The region beyond this, the "far field", is characterised by beam divergence at angles $\pm\theta$ about the central axis, given by

$$\sin \theta = 0.61\ \lambda/r \qquad (3$$

Thus, the shape of the ultrasonic field depends on the size of the transducer in relation to the wavelength. Only when the source is at least a few wavelengths in size, does the

ultrasonic field assume the shape of a defined beam. Under these circumstances, it is possible to use methods analogous to those of optics to focus the beam. The size of the focal volume is limited by the wavelength. Either lenses (made from materials which have different values of velocity from those of their surroundings) or curved, self-focusing transducers may be used. At megahertz frequencies, intensity gains of 1 000 or more may easily be achieved, corresponding to focal intensities in water of up to around 3 kW cm^{-2}.

In any given medium, the ratio of the instantaneous values of particle pressure and velocity is a constant. The constant is called the "characteristic impedance" Z of the medium, and is related to the density ρ and the velocity by the equation

$$Z = \rho c \qquad (4$$

In a propagating wave, there are no sudden discontinuities in either particle velocity or particle pressure. Consequently, when a wave meets the boundary between two media, both particle velocity and the particle pressure must be continuous across the boundary. In each medium, however, the ratio of these two quantities is fixed, being equal to the corresponding characteristic impedance; and, if the characteristic impedances of the media on each side of the boundary are unequal, the incident energy is shared to satisfy this requirement. The result is that not all the energy is transmitted across the boundary, but a fraction R is reflected which, for normal incidence, is given by the equation

$$R = [(Z_2 - Z_1)/(Z_2 + Z_1)]^2 \qquad (5$$

where Z_1 and Z_2 are the characteristic impedances of the incident and transmitting media respectively. This relationship is modified for non-normal incidence, and total internal reflection occurs where $\sin \theta_t = 1$ in the equation

$$\sin \theta_i / \sin \theta_t = c_1/c_2 \qquad (6$$

where the angles θ_i and θ_t are those of incidence and transmission respectively, as indicated in Figure 4.

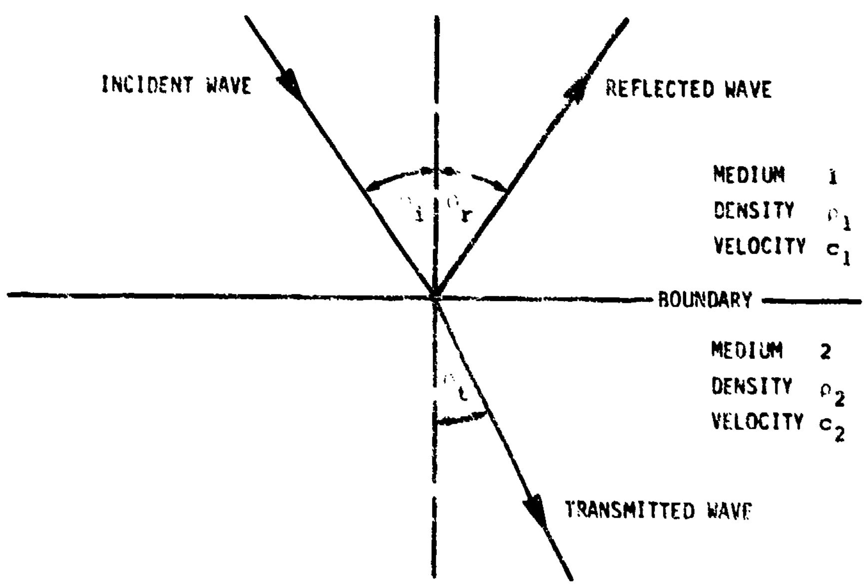

Fig. 4. Behaviour of a longitudinal wave at a boundary.

In this diagram, $\theta_i = \theta_r$, as in ray optics, and the reflection is said to be "specular". Specular reflection occurs at discontinuities in characteristic impedance which in spatial extent are large in relation to the wavelength.

It is important to realise that the results of calculations of refraction and reflection conditions at a plane boundary may not apply to a similar characteristic

impedance discontinuity at a rough interface or a small obstacle. The specular component of reflection is at least partly replaced by components of scattered energy. This effect becomes important when the dimensions of the discontinuity are of the order of a wavelength or less. If the obstacle is very much less than the wavelength in size, the intensity of the wave which is backscattered varies inversely as the fourth power of the wavelength. With wavelength-order discontinuities, however, such as may occur in biological materials, the theoretical problem becomes very difficult. It is doubtful whether models are helpful except in the elucidation of general principles, and it is better to make experimental measurements than to attempt to make theoretical estimations in cases where the physical dimensions are necessarily not well known.

Ultrasound is attenuated as it travels through a medium. The data from experimental measurements in biological materials are both sparse and hard to relate one to the other. It is not realistic, at the present time, to limit attention to tissues from man. It is seldom possible to take much account of the temperatures at which the measurements were made, nor of the "freshness" of the tissue samples, although both these factors are probably of considerable importance. Despite these limitations, it is apparent that, for biological soft tissues,

$$\alpha = a f^b \qquad (7$$

where α is the absorption coefficient (generally measured in dB cm^{-1}), and a and b depend upon the characteristics of the particular tissue and the conditions of measurement, and have fairly constant values over limited ranges of frequency. The value of b is generally only a little greater than unity for soft tissues in the frequency range 0.1 - 100 MHz, where f is expressed in MHz: typically α = 1 dB cm^{-1} MHz^{-1}, although the values range from one third to twice this rate. At 1 MHz, the absorption rate in bone is around 10 dB cm^{-1}, whilst that in lung is about 40 dB cm^{-1}. On the other hand, the absorption in blood is only 0.1 dB cm^{-1} at 1 MHz. These values may be compared with 0.0026 dB cm^{-1} in water at 1 MHz, and in water the absorption rate is proportional to the square of the frequency.

For biological soft tissues, the question arises as to how a linear relationship comes about between the absorption rate and the frequency. The "classical" mechanism of absorption, which depends on friction between the particles in the medium, gives a quadratic dependence on frequency, such as occurs in water. Of several possibilities, the theory which is presently most favoured, and for which there is considerable experimental evidence, is that biological soft tissues exhibit a broad frequency spectrum of relaxation processes. "Relaxation" is the term used to describe the behaviour of a medium in which the bulk modulus has one value for slow processes, and another for fast processes. The actual processes which may be involved have been the subject of much discussion. The most likely candidates seem to be solvent-solute interactions, and protein H-bond exchanges. The effect of a single relaxation process is to give rise to excess absorption across a band of frequency centred on the relaxation frequency. Across this band of frequency, the velocity has a slightly higher value at high frequencies than at low frequencies: this phenomenon is called "dispersion". Although a single relaxation process gives a single peak in absorption associated with one particular frequency, it turns out that the substantially linear relationship between absorption and frequency, which has been observed experimentally in soft tissues, could be accounted for by the existence of several - perhaps only four - relaxation processes with appropriate frequencies.

The absorption mechanism in bone is certainly more complicated than that in soft tissues. Scattering, and conversion to shear waves of short range, are likely to be important factors. The dependence on frequency is quadratic at frequencies below about 2 MHz, but it is more nearly linear at higher frequencies. Different kinds of bone have different properties; and the behaviour of compact ivory bone, for example, is relatively free from these complexities. The velocity in bone is about three times

faster than that in soft tissues, and the density is up to twice as much. Consequently, the characteristic impedance of bone may be five or six times greater than that of soft tissues.

The absorption in lung is even greater than that in bone, but the velocity is only about half that in soft tissues. The high rate of absorption may be due to the re-radiation of energy by pulsating gaseous structures in the lung tissue, whilst the low velocity is also due to the presence of gas (in which the velocity is only about 300 m s^{-1}).

The incidence of occurrence of gas bubbles within liquids or soft tissues may have profound effects on the neighbouring ultrasonic field, due to phenomena broadly classified as cavitation effects. If a bubble already exists in a medium, it may be set into resonant oscillation by the application of an ultrasonic field which has a frequency appropriately related to the dimensions of the bubble. For an air-filled bubble in water at atmospheric pressure,

$$f_r \; r_b \approx 3.3 \qquad (8$$

where f_r is the resonance frequency (in Hz), and r_b is the bubble radius (in m). For example, a bubble of 50 μm radius would resonate at a frequency of about 66 kHz.

Quite steep gradients in the ultrasonic field can occur near resonating bubbles. These gradients can give rise to streaming, which can exist in any of several régimes according to the ultrasonic amplitude. Similar gradients may also be generated near the tip of a needle set into longitudinal vibration by an appropriate transducer. Generally these effects are observed at relatively low intensities, and the behaviour of bubbles changes only slowly if at all, the phenomenon being known as "stable" cavitation.

At high intensities, the negative pressure during the wave cycle may be sufficient to disrupt the supporting medium. Transient cavitation is the phenomenon in which voids suddenly grow and then collapse in the supporting liquid. The collapse of the cavity leads to strong pressure pulses, or shock waves, in the supporting liquid. The whole process occupies an interval of less than that of one cycle of the wave.

Cavitation, either stable or transient, may be suppressed by degassing the medium or by increasing the external pressure applied to the system. It is also inhibited by increasing the viscosity of the supporting liquid, and by reducing the time duration of the irradiation.

Although much is understood concerning the effects of cavitation on biological materials in liquids, either in solution or in suspension, it is still to some extent a matter of speculation as to whether or not stable cavitation occurs in soft tissues. At very high intensities, transient cavitation certainly can occur. The question which needs to be answered is whether or not micron-sized bubbles exist in soft tissues which could be set into stable cavitation by low-intensity, megahertz-frequency ultrasound.

For further reading

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BIOPHYSICS - ENERGY ABSORPTION AND DISTRIBUTION

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SUMMARY

The interpretation of the biological effects observed in tissues exposed to EM fields requires a complete quantitative description of the fields within the tissues. These fields are complex functions of the source configuration, shape and size of the exposed subject, and the frequency. The average and maximum absorbed power density may vary over many orders of magnitude for the same applied field intensities. Depending on conditions, power absorption may be predominantly at the surface of the subject or may be affecting only superficial tissues in the interior of the subject affecting deep tissues.

A. INTRODUCTION

The total amount and the distribution of the absorbed electromagnetic power in biological tissue exposed to electromagnetic fields (EM) is a function of many factors, including the magnitude of the electric field (E), magnitude of the magnetic field (H), the relative stored energy in the magnetic and electric fields, the source and tissue configurations, the tissue composition, frequency, environmental factors, and others. Therefore, in general, it is impossible to establish any meaningful relationships between a simple measurement of the external E and H fields and observable biological effects in a subject exposed to EM fields. We could expect, however, to establish a useful association between the measured internal electric field, E_i, and the effect because of its obvious relationship to absorbed power, W (per unit mass in the tissues), induced current density, J, or other identifiable quantities that directly interact with the tissues. Furthermore, one would expect that once this association is established for a particular biologic tissue or system, it could be related much more meaningfully with other tissues or systems.

The absorption, diffraction, and scattering effects of the test animal or specimen in the field are considerably different than the same effects pertaining to exposure of man. The greatest complicating factors result from interference patterns within the tissues which produce regions of intensifications of absorbed power or hot spots in regions of low absorbed power within a given animal. These absorbed power patterns will vary depending on the source, frequency, body size, geometry, and the environment around the subject. The only practical way to accurately quantify biologic damage or therapeutic benefits in terms of incident power levels is to relate them to the internal field and absorbed power distributions. Much of the research pertaining to biological effects is done through animal experimentation or irradiation of biologic specimens in vitro. The question is, how do we relate the effects to the fields and extrapolate the results of these to the radiation effects in humans. In the controlled animal or biologic tissue we have the option to set up any field configuration we desire, whether a radiation field or a near-zone field situation, where an effective power density level produces quantifiable effects of damage or benefits in the animal or specimen, similar effects or damage can occur in the human with the same effective power. With exposure of the animal or specimen, we also have scattering, absorption, and internal reflections that are uniquely associated with the animal's body and tissue characteristics or the specimen's geometry that result in absorbed power densities different from that for human exposure.

The most sensible approach is to quantify the actual fields, or absorbed energy in the tissues or specimen, and relate this finding to the biologic effects, damage or benefits that may occur. Once this information is available, the next task is to determine what incident power or outside field, whether predominantly a radiation, electric or magnetic field, will produce the same effect in man. The essentials to know, then, are what level of power per unit volume or mass absorbed by the tissue in an animal or specimen under irradiation will yield an effect, damage, or benefit, and what level of power or field as measured by a survey meter will produce the same absorbed power in human tissues. These questions can be answered only through the application and development of porper measurement techniques. Only then will a clear understanding be determined of how EM fields interact with the tissue, whether on a microscopic or macroscopic scale, or on the entire body structure, or whether an observable effect is thermal or non-thermal in origin or is merely an artifact to the nature of the experimental approach. By taking proper account of body size of the experimental animal, along with accurate in vivo dosimetry, the results from an investigator using rats can be related to those from another study on cats, monkeys, dogs, frogs, or tissue sample in a test tube.

B. DIELECTRIC PROPERTIES AND EM WAVE PROPAGATION THROUGH BIOLOGICAL TISSUES

Some of the basic characteristics of EM field interaction with biological materials can be characterized by the wave parameters tabulated in Tables I and II. The first column lists selected frequencies between 1 MHz and 10 GHz. Frequencies of 27.12, 40.68, 433, 915, 2450 and 5800 MHz are significant since they are used for industrial, scientific, and medical heating processes. The frequencies of 27.12, 433, 915 and 2450 MHz are used for diathermy purposes. The second column tabulates the corresponding wavelength λ in air, and the remaining columns pertain to the wave properties of a particular tissue group. Table I gives data for muscle, skin or tissues of high water content, while Table II is for fat, bone and tissues of low water content. Other tissues containing intermediate amounts of water such as brain, lung, bone marrow, etc., will have properties that lie between the tabulated values for the two listed groups. The tables list the dielectric properties, the depth of penetration, and the reflection characteristics of various tissues exposed to EM waves as a function of frequency.

The dielectric behavior of the two groups of biological tissues tabulated in Table I and II has been evaluated most thoroughly by Schwan and his associates [1]-[3] and by other researchers including Cook [4]-[6] and Cole [7]. The interaction of EM wave fields with biological tissues is related to these dielectric characteristics. The tissues are composed of cells encapsulated by thin membranes containing an intracellular fluid composed of various salt ions, polar protein molecules, and polar water molecules. The extracellular fluid has similar ions and polar molecules, though some of the elements are different.

The action of electromagnetic fields on the tissues produces two types of effects that control the dielectric behavior. One is the oscillation of the free charges or ions, and the other the rotation of dipole molecules at the frequency of the applied electromagnetic energy. The first gives rise to conduction currents with an associated energy loss due to electrical resistance of the medium, and the other affects the displacement current through the medium with an associated dielectric loss due to viscosity. These effects control the behavior of the complex dielectric constant $\epsilon^*/\epsilon_o = (\epsilon' - j\epsilon'')$, where ϵ_o is the permittivity of free space, ϵ^* is the complex permittivity, ϵ' is the dielectric constant, and ϵ'' is the loss factor of the medium. The effective conductivity σ (due to both conduction currents and dielectric losses) of the medium is related to ϵ'' by $\epsilon'' = \sigma/\omega\epsilon_o$ and the loss tangent is given by $\tan\delta = \epsilon''/\epsilon' = \sigma/\omega\epsilon'\epsilon_o$. The quantity ϵ^* will be dispersive due to the various relaxation processes associated with polarization phenomena. These are indicated by the dielectric properties given in Tables I and II. The decrease in dielectric constant ϵ_H and increase in conductivity σ_H for tissues of high water content with increasing frequency is due to interfacial polarization across the cell membranes. The cell membranes, with a capacity of approximately 1 µF/cm², act as insulating layers at low frequencies so that currents flow only in the extracellular medium, accounting for the low conductivity of the tissues. At sufficiently low frequencies, the charging time constant is small enough to completely charge and discharge the membrane during a single cycle, resulting in a high tissue capacitance and therefore a high dielectric constant. When frequency is increased, the capacitive reactance of the cell decreases, resulting in increasing currents in the intracellular medium with a resulting increase in total conductivity of the tissue. The increase in frequency will also prevent the cell walls from becoming totally charged during a complete cycle, resulting in a decrease of ϵ_H. At a frequency of approximately 100 MHz and above, the cell membrane capacitive reactance becomes sufficiently low that the cells can be assumed to be short-circuited. In the frequency range of 100 MHz to 1 GHz, the ion content of the electrolyte medium has no effect on the dispersion of the dielectric constant so the values of ϵ_H and σ_H are relatively independent of frequency. Schwan [1],[8] has suggested, however, that suspended protein molecules with a lower value of dielectric constant act as "dielectric cavities" in the electrolyte, thereby lowering the dielectric constant of the tissue. He attributes the slight dispersion of ϵ_H to the variation of the effective dielectric constant of the protein molecules with frequency. The final decline of ϵ_H and increase of σ_H at frequencies above 1 GHz can be attributed to the polar properties of water molecules which have a relaxation frequency near 22 GHz.

The dielectric behavior of tissues with low water content is quantitatively similar to tissues with high water content, but the values of dielectric constant ϵ_L and conductivity σ_L are an order of magnitude lower and are not quantitatively understood as well. This is due to the fact that the ratio of free to various types of bound water is not known. There is also a large variation in tissues of low water content. Since water has a high dielectric constant and conductivity compared to fat, the net tissue dielectric constant and conductivity will change significantly with small changes in water content.

The values of σ and ϵ will also vary with temperature. In the microwave region, where dispersion is small, the variation is given by $\frac{\Delta\sigma}{\sigma} = 2\%/°C$ and $\frac{\Delta\epsilon}{\epsilon} = -0.5\%/°C$. The dielectric properties of the tissues play an important part in determining the reflected and transmitted power at interfaces between different tissue media. They also determine the amount of total power a given biological specimen will absorb when placed in an electromagnetic field.

Plane wave propagation characteristics in plane layered biological tissues may be examined to show how radiation is absorbed when the radius of curvature of the tissue surface is large compared to a wavelength. The propagation constant $k_{H,L}$ for power transmission through biological tissues can be written in terms of the complex dielectric constants $\epsilon^*_{H,L}$ and free space propagation constant k_o in the standard form,

$$k_{H,L} = k_o(\epsilon^*_{H,L}/\epsilon_o)^{1/2} = \beta_{H,L} - j\alpha_{H,L} \tag{1}$$

where the wavelengths $\lambda_{H,L} = 2\pi/\beta_{H,L}$ are significantly reduced in the tissues due to the high dielectric constants. Tables I and II indicate that the factors of reduction are quite large, between 6.5 and 8.5, for tissues of high water content, and between 2 and 2.5 for tissues with low water content. In addition to the large reduction in wavelength, there will be a large absorption of energy in the tissue which can result in heating. The absorbed power density $W_{H,L}$ resulting from both ionic conduction and vibration of dipole molecules in the tissues is given by

$$W_{H,L} = \frac{\sigma_{H,L}}{2}\,|E|^2 \tag{2}$$

where E is the magnitude of the electric field. One may note from the conductivities listed in Tables I and II that absorption in tissue of higher water content may be as high as 60 times greater than in that of low water content for the same electric fields. The absorption of microwave power will result in a progressive reduction of wave power density as the waves penetrate into the tissues. We can quantify this by defining a depth of penetration $d = 1/\alpha$, or a distance that the propagating wave will travel before the power density decreases by a factor of e^{-2}. We can see from Tables I and II that the depth of penetration for tissues of low water content is as much as 10 times greater than the same parameter for tissues of high water content.

Since each tissue in a complex biological system such as man has different complex permittivity, there will in general be reflections of energy between the various tissue interfaces during exposure to microwaves. The complex reflection coefficient due to a wave transmitted from a medium of complex permittivity ϵ_1^* to a medium of permittivity ϵ_2^* and thickness greater than a depth of penetration is given by

$$\rho = re^{j\phi} = \frac{\sqrt{\epsilon_1^*} - \sqrt{\epsilon_2^*}}{\sqrt{\epsilon_1^*} + \sqrt{\epsilon_2^*}} \tag{3}$$

The values r and ϕ for various interfaces are tabulated in Tables I and II. Note the large reflection coefficient for an air-muscle or a fat-muscle interface. When a wave in a tissue of low water content is incident on an interface with a tissue of high water content of sufficient thickness (greater than the depth

of penetration), the reflected wave is nearly 180° out of phase with the incident wave, thereby producing a standing wave with an intensity minimum near the interface. If the wave is propagating in a tissue of high water content and is incident on a tissue of low water content, the amplitude of the reflected component is in phase with the incident wave, thereby producing a standing wave with an intensity maximum near the interface. If there are several layers of different tissue media with thicknesses less than the depth of penetration for each medium, the reflected energy and standing wave pattern are influenced by the thickness of each layer and the various wave impedances. These effects may be obtained from the standard transmission line equations. The distribution of electric field strength E in a given layer is

$$E = E_0 (e^{-jkz} + \rho e^{jkz}) \tag{4}$$

where E_0 is the magnitude of the field and ρ is the reflection coefficient. From (2), the equation for absorbed power density in the tissue layer, we obtain

$$W = \frac{|E_0|^2}{2} [e^{-2\alpha z} + r^2 e^{2\alpha z} + 2r \cos (2\beta z + \phi)]. \tag{5}$$

Schwan [1],[9] has made extensive calculations of these absorption distributions in various tissues. Typical distributions are shown in Fig. 1 for a wave transmitted through a subcutaneous fat medium into a muscle medium. The absorption is normalized to unity in the muscle at the fat-muscle interface. The relative absorption curves shown remain unchanged for smaller fat thicknesses. The severe discontinuity between the absorbed power in the muscle and that in the fat is quite apparent. Also, it can be seen that the standing wave peaks become larger in the fat and the wave penetration into the muscle becomes less with increasing frequency. This illustrates clearly the desirability for using frequencies lower than the 2450 MHz allocation for diathermy. Subcutaneous fat may vary from less than a centimeter in thickness to as much as 2.5 cm for different individuals. Deep heating for diathermy requires the transmission of energy through this subcutaneous fat layer to the muscle layer. Optimum results are attained with maximum heating in the muscle. The absolute values of absorbed power density in the tissue layers are dependent on incident power density, skin thickness, and fat thickness.

Fig. 2 illustrates the absorbed power density at the muscle interface and the peak absorbed power density in a skin layer 2 mm thick as a function of fat thickness for an incident power density of 1 mW/cm^2. These values may be used to determine the absorbed power at other locations in the muscle and fat by relating them to the curves in Fig. 1. The peak absorbed power density is always maximum in the skin layer for the plane layered model. This is significant since the thermal receptors of the nervous system are located there and will indicate pain when the incident power density reaches levels that could thermally damage the tissue. With surface cooling of the skin, however, by natural environmental conditions or by controlled clinical procedures, the temperature increases may be higher in the fat or muscle. The peak absorption in the various tissues may vary over a wide range with fat thickness and frequency. It is apparent that frequencies below 918 MHz can penetrate more deeply into the tissue. The implications of this in terms of both radiation hazards and therapeutic applications are apparent. The first two figures clearly indicate the advantages of lower frequencies for diathermy, including 1) increased penetration into the muscle tissue, 2) less severe standing waves and resulting "hot spots" in the fat, and 3) better control and knowledge of the absorbed energy for a given incident power for a large variation of fat thicknesses between different patients.

There is a practical lower limit, however, on the frequency that can be used. As the frequency is decreased, the applicator needed becomes increasingly large until it is no longer possible to obtain desired selective heating patterns. If the applicator is not increased in size as frequency is lowered, only superficial heating will result. This has been discussed in detail by Guy and Lehmann [10] and Guy [11].

A problem of interest in diathermy is the determination of how effective microwaves are in heating a layer of bone beneath a layer of subcutaneous fat and muscle. Fig. 3 illustrates heating patterns for this case using diathermy frequencies of 2450 MHz and 918 MHz for a 2 cm thick bone. The results clearly show that the absorption in the bone is very poor due to both a severe reflection and a low electrical conductivity. Since a standing wave peak at 918 MHz occurs in the muscle near the bone surface, we would expect significant bone heating due to thermal conduction from the muscle.

C. THERMAL CONSIDERATIONS

The energy equation for the time rate of change of temperature (°C/sec) per unit volume of subcutaneous tissue in a subject exposed to EM fields is

$$\frac{d(\Delta T)}{dt} = \frac{0.239 \times 10^{-3}}{c} [W_a + W_m - W_c - W_b] \tag{6}$$

where W_a is the absorbed power density, W_m is the metabolic heating rate, W_c is the heat loss due to thermal conduction, W_b is the power dissipated by blood flow, all expressed in W/kg, c is the thermal conductivity expressed in kcal/kg·°C, and $\Delta T = T - T_0$ is the difference between tissue temperature T and the initial temperature T_0. The absorbed power density for tissue exposed to an EM field is

$$W_a = 10^{-3} \sigma |E|^2 / \rho \tag{7}$$

where σ is the electrical conductivity in mhos/meter, ρ is the tissue density in g/cm^3, and E is the rms value of the electric field (V/m) in the tissue. If it is assumed that blood enters the tissue at arterial temperature T_a and leaves at tissue temperature T, we may express blood cooling by $W_b = k_2 m c_b / \rho_b \Delta T'$ where $\Delta T' = T - T_a$, c_b is the specific heat of blood, ρ_b is the density of blood, m is the blood flow rate in ml/100 g·m, and the constant $k_2 = 0.698$. Prior to the time the tissue is exposed to fields, it is assumed that a steady state condition exists where $W_a = d(\Delta T)/dt = 0$ requiring $W_m = W_c + W_b$. According to the typical values of the physical and thermal properties of tissues given in Table III, under normal conditions the metabolic rate W_m averages 1.3 W/kg for the total body, 11 W/kg for brain tissue, and 33 W/kg for heart tissue. According to the energy equation, we would expect to see some change in tissue temperature due to applied EM fields if the power absorption density W_a were of the same order of magnitude as W_m, or more. In fact, the safety guides in the United States that allow a maximum human exposure level of 10 mW/cm^2 of incident

power are partially based on limiting the average W_a to the average resting value of W_m. Thus, absorbed power densities $W_a >> W_m$ could be expected to produce marked thermal effects, whereas, power densities $W_a << W_m$ would not be expected to produce any significant thermal effects.

D. RELATIONS BETWEEN PLANE WAVE FIELDS AND ABSORBED POWER DENSITY IN EXPOSED BIOLOGICAL OBJECTS

We have already discussed a case in the previous section for the absorbed power distributions in planar layered tissues exposed to plane wave fields. Considerable insight can be gained into the relationship between frequency, body size, and absorbed power by considering spherical tissue layers exposed to a plane wave. Fig. 4 illustrates the relative absorbed power density patterns for various spherical tissue geometries exposed to a 1 mW/cm^2 plane wave source. The origin of the rectangular coordinate system in the figures is located at the center of the sphere with wave propagation along the z axis and the E field polarized along the x axis. The maximum absorption and the average absorption density are tabulated on each plot. When the diameter of the exposed object is of the order of one wavelength as measured in the tissue, severe internal wave interference produces sharp maxima and minima in the power absorption patterns, as shown in Fig. 4-a, for a sphere representing a human head exposed to 918 MHz radiation. The spherical model is composed of an inner core consisting of brain tissue surrounded by a layer of bone and skin. When the object is large compared with a wavelength, as measured in the tissue, the maximum absorption occurs at the exposed surface, decaying nearly exponentially with depth, as shown in Fig. 4-b for a homogeneous muscle sphere with the same mass as a 70 kg man exposed to 918 MHz radiation. When the exposed subject is very small compared with a wavelength, but of a mass approximating that of man, the power absorption density varies nearly as the square of distance from the y axis (direction of magnetic field vector), as shown in Fig. 4-c. On the other hand, if the object is very small compared with a wavelength, but with a mass very small compared to that of man, the power absorption density is uniform along the y axis but increases with distance toward the exposed surface and decreases with distance toward the opposite surface, as shown in Fig. 4-d. The latter two absorption patterns for objects small compared with a wavelength can be explained from simple quasi-static field theory [12].

The electric field component of the incident plane wave couples to the object in the same manner as a static electric field giving rise to a constant internal electric field which is $3/\epsilon^*$ times smaller, and in the same direction as the applied field, where $\epsilon^* >> 1$ is the dielectric constant of the tissue. Superimposed on the constant internal electric field is another magnetically induced electric field component encircling the y axis, as shown in Fig. 5. The magnitude of the latter field, which varies directly with radial distance r from the axis, and directly with frequency f, is given by $E = \pi f r \mu H$, where H is the magnetic field. The H-induced E field component in a sphere with the same mass as man is much greater than the E-induced component, whereas, for a small object with the mass of a small rodent, both components are significant. The variation of the maximum and average power absorption density with frequency for an exposed homogeneous muscle sphere with the same volume is shown in Fig. 6. Also shown in the figure is the average power absorption density per unit total surface area of the sphere. In the frequency range from 1 MHz to 20 MHz, the absorption characterized by the pattern in Fig. 4-c varies as the square of the frequency. This is due primarily to the magnetically induced fields.

The maximum power absorption density induced by the incident H field is denoted by the curve marked with crosses, and that due to the incident E field is denoted by the curve with zeros in the range where the quasi-static coupling approximations apply. Note that in this range, the maximum power absorption density is only 10^{-5} to 10^{-2} W/kg per mW/cm^2 of incident power. In the frequency range 100 to 1000 MHz, internal reflections are significant for the man-size sphere and the average absorption attains a maximum of 2×10^{-2} W/kg per mW/cm^2 of incident power at 200 MHz, which remains relatively constant with frequency up to 10 GHz. The maximum absorption density increases with frequency above 1000 MHz, approaching that produced by non-penetrating radiation. The dashed lines illustrate roughly the frequency dependence of the total or average absorbed power and how safety standards might be relaxed as a function of frequency if the absorption characteristics in man were the same as for the sphere. The wide variation of absorption characteristics with body size is illustrated in Fig. 7 for a sphere consisting of an inner muscle core surrounded by concentric layers of subcutaneous fat and skin exposed to 2450 MHz plane wave 1 mW/cm^2 radiation. The total radius, fat thickness and skin thickness are noted on the figure. It is significant to note that based on the spherical models, the peak power absorption could be as high as 4.2 W/kg in the body or head of a small bird or animal but as low as 0.27 W/kg at the surface, and 0.05 W/kg 2.5 cm deep in the human body exposed to a 1 mW/cm^2, 918 MHz source (Fig. 4-b). Thus, 10 mW/cm^2 could be of extreme and 0.5 mW/cm^2 could be of mild thermal significance to the smaller animal in comparison with metabolic rate. For the human model, on the other hand, 10 mW/cm^2 would appear to be of mild thermal significance and 0.5 mW/cm^2 would have negligible thermal significance.

Power absorption density patterns may also be calculated for other simple tissue geometries representing portions of the anatomy. We can roughly approximate human limbs by concentric cylindrical layers of bone, muscle, fat, and skin and express the fields in each layer by an infinite series of Bessel functions of the first and second kind as discussed by Stratton [13], pp. 349-374]. For example, the electric field parallel to the z axis of the cylinder is expressed as

$$E_z = \sum_{n=0}^{\infty} [A_n J_n(kr) + B_n Y_n(kr)] e^{jn\theta} \tag{8}$$

where k is the wave number in the medium and the coefficients A_n and B_n are obtained by expanding the plane wave source expression into a series of Bessel functions and applying boundary conditions. Similar equations may be written for the wave polarized with the magnetic field parallel to the z axis. Ho, et al., [14] have evaluated the equations and determined the fields and absorbed power densities for cylinders corresponding to human arms and legs exposed to plane waves. The results illustrated, along with measured values in Figs. 12, 15 and 16 in "Engineering Considerations and Measurements" of this series, show the same increase in muscle-to-fat absorbed power density with decreasing frequency as observed for exposed planar models. The results show an even greater depth of energy penetration into the cylindrical muscle model than for the semi-infinite model discussed previously.

E. QUASI-STATIC FIELD COUPLING TO SPHERES AND ELLIPSOIDS

It was illustrated in Section D that the induced electric fields in a spherical tissue model exposed to a plane wave consists of the superposition of two components which may be expressed by

$$\underline{E}_t = E_o e^{-j\omega t}\left[\frac{3}{\varepsilon^{*}}\,\hat{\underline{x}} - j\frac{kR}{2}\left(\cos\phi\,\hat{\underline{\theta}} - \cos\theta\sin\phi\,\hat{\underline{\phi}}\right)\right] \tag{9}$$

where ω is the angular frequency, $\varepsilon^{*} = \varepsilon - j\frac{\sigma}{\omega\varepsilon_o}$ is the complex dielectric constant, ε_o is the permittivity of space, k is the free space propagation constant, R,θ,ϕ are the coordinates of a spherical coordinate system, and x the usual rectangular coordinate, all with an origin at the center of the sphere. The hats over the coordinates represent the usual unit vectors, and E_o is the electric field strength of an incident plane wave.

The field is a simple superposition of two field components, the first induced by the electric field independent of the magnetic field component, and the second term induced by the magnetic field independent of the electric field component. The first term corresponds to an electric field distributed uniformly throughout the volume, while the second is a circular electric field pattern about the y axis of the sphere which varies linearly in amplitude with the radial distance from the axis. For a tissue sphere equivalent in volume to that of man exposed to plane wave fields, the magnetically induced term is usually an order of magnitude greater than the electrically induced term. Taken separately, an electric field will produce uniform power absorption density and the magnetic field would produce a power absorption density pattern varying with the square of the radial distance from the sphere axis parallel to the magnetic field.

Similar type equations may be derived for dielectric ellipsoids exposed to quasi-static electromagnetic fields (small compared to a wavelength in ellipsoid and surrounding medium). The electric field, E_i, coupled to a dielectric ellipsoid due to an applied unit field is given by Weber [15] as

$$E_i = \left[1 + \left(\frac{\varepsilon_i^{*}}{\varepsilon_o^{*}} - 1\right)(u_o^2 - 1)(u_o \coth^{-1} u_o - 1)\right]^{-1} \tag{10}$$

for an applied field parallel to the major axis and

$$E_i = \left\{1 + \left(\frac{\varepsilon_i^{*}}{\varepsilon_o^{*}} - 1\right)\frac{u_o}{2}\left[u_o - (u_o^2 - 1)\coth^{-1} u_o\right]\right\}^{-1} \tag{11}$$

for a field perpendicular to the major axis where

$$u_o = \cosh[\tanh^{-1} a/b] \tag{12}$$

and a = the major semi-axis, b = the minor semi-axis of the ellipsoid, ε_o^{*} = the complex dielectric constant of the medium, and ε_i^{*} is the complex dielectric of the ellipsoid. One may note that the internal field is uniform as for the case of the sphere and $E_i \to 1$ the value of the outside field for the first case, and $E_i \to 2\left(\frac{\varepsilon_i^{*}}{\varepsilon_o^{*}} + 1\right)^{-1}$ for the second case when $b/a \to 0$. Thus, for the case where the electric field is parallel to an elliptical tissue geometry with small values of b/a, the electric field coupling can become very large. Fig. 8 illustrates absorbed power due to an electric field coupling as a function of b/a, frequency, and polarization for ellipsoids composed of muscle-type dielectric exposed to a 1 mW/cm^2 radiation field (E_o = 61.4 V/m). For $b/a < 10^{-1}$ the absorption increases two orders of magnitude or greater over that due to the electric field coupling to a sphere (b/a = 1).

It is important to note that even though the uniform inner field approaches the applied field when $b/a \to 0$ (simulating a thin rod) that continuity of the normal displacement current requires that at the poles of the ellipsoid a local field strength of

$$E_n = \frac{\varepsilon_i^{*}}{\varepsilon_o^{*}} E_i + \frac{\varepsilon_i^{*}}{\varepsilon_o^{*}} E_o \tag{13}$$

will exist. Thus, we would expect strong concentration of electric field strength to exist on high dielectric constant or highly conducting objects such as wires, electrodes, or sharp objects implanted in tissue. This will be discussed in Section F of this series.

The power absorption characteristics due to combined electric and magnetic fields were obtained by Durney, et al., [16] for ellipsoids. When the electric field is parallel to the major axis of the ellipsoid, and the magnetic field is parallel to the minor axis, the induced internal field for an incident plane wave with a unit electric field is

$$\underline{E} = B_e\,\hat{\underline{z}}[-j\sigma/\omega\varepsilon_o]^{-1} - jk[u_{10}^2\, y\hat{\underline{z}}/(2u_{10}^2 - 1) + (1 - u_{10}^2)\, z\hat{\underline{y}}/(2u_{10}^2 - 1)] \tag{14}$$

where

$$B_e = [u_{10}^2 - 1]^{-1}\left[(u_{10}/2)\ln[(u_{10} + 1)/(u_{10} - 1)] - 1\right]^{-1} \tag{15}$$

$$u_{10} = a/\sqrt{a^2 - b^2} \tag{16}$$

and the (x,y,z) coordinate system is centered in the ellipsoid with the z axis along the major axis and the x axis along a minor axis, and again, as for the spherical case, the total field is a combination of a

uniform field induced by the electric field (first term of Eq. 14) and a circulating eddy current field induced by the magnetic field (the second term of the equation). For this case, however, the uniform electric field induced component is much larger with increased axial ratio b/a.

F. FIELD COUPLING FROM FINITE SOURCES

1. Aperture Sources

If other than a plane wave source is used to expose biological tissues, the absorbed power density patterns are also very dependent on source size and distribution. Many applications of microwave power in medicine and studies on the biological effects of microwave power require an understanding of the absorbed power patterns due to tissues exposed to aperture and waveguide sources. Guy [11] has analyzed the case where a bilayered fat and muscle tissue layer is exposed to a direct contact aperture source of width a and height b. A fat tissue layer of thickness z_1 and dielectric constant ϵ_f^* in contact with a semi-infinite muscle layer with a dielectric constant ϵ_m^* is assumed. The origin of the coordinate system is located at the center and in the plane of the aperture with the x axis parallel to height b and the z axis in the direction of propagation into the tissue. The electric fields $\underline{E}_{f,m}$ in the fat and muscle tissue may be expressed as Fourier integrals

$$\underline{E}_{f,m}(x,y,z) = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \underline{T}_{f,m}(u,v,z)e^{j(ux+vy)}dudv \tag{17}$$

where $\underline{T}_{f,m}$ are the Fourier transforms of the electric fields at the fat and muscle boundaries, derived from the boundary conditions at $z = 0$ and $z = z_1$ in terms of the Fourier transform of the aperture

$$\underline{T}_a(u,v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \hat{\underline{z}} \times \underline{E}_i(x,y,0)e^{-j(ux+vy)}dxdy \tag{18}$$

The aperture field is denoted as $\underline{E}_f(x,y,0)$ and $\hat{\underline{z}}$ is a unit vector along the z axis. The expressions may be evaluated numerically and the absorption patterns plotted by means of a digital computer. As an example, we may consider a waveguide aperture source and evaluate it as a diathermy applicator for use at 918 MHz. Fig. 9 illustrates the complete heating curves in the x-z plane for a = 12 cm and b = 2, 4, 12, and 26 cm. Heating at the fat surface for a plane wave exposure is denoted by the dashed line on the figures. The results show that the relative heating varies from intense superficial heating in excess of that produced by a plane wave to deep heating greater than that produced by a plane wave as aperture size is increased.

The absorbed power density patterns in multilayered cylindrical tissues exposed to an aperture source can also be determined by using a summation of three-dimensional cylindrical waves, expressing the aperture field as a two-dimensional Fourier series and matching the boundary conditions. Ho, et al., [17],[18] have calculated the absorbed patterns for a number of different aperture and cylinder sizes. Typical results are shown in Fig. 10 for a human arm-size cylinder exposed to a surface aperture source 12 cm long in the direction of the axis. The patterns are plotted as a function of radial distance from the center of the cylinder for various circumferential angles ϕ from the center of the aperture. The patterns are normalized to the values at $\phi = 0°$ at the muscle interface. The difference between the patterns in the cylindrical tissues and those illustrated for the plane layers indicates the importance of tissue curvature when assessing the effectiveness and safety devices designed for medical application of microwave energy.

All of the theoretical results discussed in this section strongly point to the ineffectiveness of the 2450 MHz frequency as a diathermy frequency as pointed out in earlier reports by Schwan [1],[2], Lehmann [19], and Guy, et al., [11],[20]. Although the lower frequencies of 915 MHz authorized in the United States or 433 MHz authorized in Europe appear to be better choices, it appears from the theoretical data that 750 MHz would be the best choice. By their nature the frequencies that provide the best therapeutic heating would also be frequencies that could be most hazardous to man in an uncontrolled situation.

2. Lumped Inductor Source

The type of source that has been used frequently in shortwave diathermy is an inductive coil designed to induce 27.12 MHz eddy currents in tissues by magnetic induction. A great deal of insight and some quantitative information concerning absorbed power can be gained through a simple theoretical analysis of the coupling characteristics of the applicator to tissue. The applicator can be analyzed by considering the case of planar skin, fat and muscle geometry exposed to a flat pancake coil with coordinates and parameters as defined in Fig. 11. Since the size of the coil is small compared to the 11 meter wavelength, the mathematics can be greatly simplified by approximating the actual spiral coil with perfect concentric loops connected in series and assuming quasi-stationary field conditions [21]. The vector potential, A_ϕ, and magnetic field, H_z, of the coil are

$$A_\phi = \frac{\mu I}{\pi(\rho)^{1/2}} \sum_{i=1}^{n} \frac{(a_i)^{1/2}}{k_i} \left[(1 - \frac{1}{2} k_i^2) K(k_i) - E(k_i)\right] \tag{19}$$

$$H_z = \frac{I}{4\pi(\rho)^{1/2}} \sum_{i=1}^{n} \frac{k_i}{(a_i)^{1/2}} \left[K(k_i) + \frac{a_i^2 - \rho^2 - (z + h)^2}{(a_i - \rho)^2 + (z + h)^2} E(k_i)\right] \tag{20}$$

where

$$k_i^2 = \frac{4\rho a_i}{(\rho + a_i)^2 + (z + h)^2} \tag{21}$$

and where $K(k_i)$ and $E(k_i)$ are complete elliptical integrals of the first and second kind, a_i is the radius of the ith loop, n is the number of loops, I is the loop current, μ is the permeability of free space, and ρ and z are cylindrical coordinates of the point of observation. The magnetically induced electric field

component E_ϕ may be expressed as $E_\phi = j\omega A_\phi$, which at shortwave diathermy frequencies can be assumed to penetrate the tissues without significant perturbation since the tissues are nearly transparent to the near-field inductive components of the coil.

The major field component induced in the subcutaneous fat due to the voltages, A_i, of the coil is normal to the interfaces given by

$$E_z = \frac{1}{|\varepsilon_o^*|} \sum_{i=1}^{n} A_i \left\{ \frac{2h}{[(\rho + a_i)^2 + h^2]^{3/2}} \left[K(k_i) - \frac{4\rho a_i}{(\rho - a_i)^2 + h^2} B(k_i) \right] \right\} \quad (22)$$

in the fat where

$$B(k_i) = \frac{E(k_i)}{k_i^2} - \frac{1 - k_i^2}{k_i^2} K(k_i) \quad (23)$$

and k_i is simply Equation 21 evaluated at $z = 0$.

If we ignore the field spreading and other quasi-static field components because of the close proximity of the fat-muscle interface, we may obtain an estimate of the absorbed power in the fat

$$W_a = \frac{\sigma_f}{\rho_f} [E_z^2 + E_\phi^2] \times 10^{-3} \quad (24)$$

due to both the induction field and the significant component of the quasi-static field.

When evaluating Eq. 24, one should keep in mind that the most desirable heating or absorption patterns for therapeutic purposes corresponds to minimum relative heating in the fat with maximum relative heating and depth of penetration into the muscle. Fig. 12 illustrates the calculated results for tissues exposed to a flat coil with the same wire thickness and radii of turns as a typical commercial applicator. Three concentric loops provide the closest approximation for this case. With such few turns, it is more convenient to assume that the total applied voltage calculated from the coil current and inductance was distributed equally between the center and the inner and outer loops. A coil current of 1 A, a fat thickness of $z_1 - 2$ cm and a spacing of 3 cm between the applicator coil and the surface of the fat are assumed. The results show that the coil induces a toroidal heating pattern with a maximum heating of 0.665 W/kg in the muscle at a radial distance $\rho = 5.5$ cm from the coil axis with a penetration depth (depth where heating drops by a factor of e^{-2} from the maximum) into the muscle of about 4 cm. The maximum heating in the fat which occurs on the axis is approximately one-third that of the muscle. A second lower peak occurs in the fat at $\rho = 5.8$ cm. The former is due to the coupling from the electric field induced by magnetic coupling. The value of heating for other values of coil current may be obtained by multiplying the results given in the figure by the square of the coil current. The value of coil current varies according to the power output setting of the generator, the spacing between the coil and the patient, and the geometry of the exposed tissue.

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TABLE I Properties of Microwaves in Biological Media*

		Muscle, Skin, and Tissues with High Water Content							
Frequency (MHz)	Wavelength in Air (cm)	Dielectric Constant (ϵ_H)	Conductivity σ_H (mhos/meter)	Wavelength λ_H (cm)	Depth of Penetration (cm)	Reflection Coefficient Air-Muscle Interface		Reflection Coefficient Muscle-Fat Interface	
						r	ϕ	r	ϕ
1	30,000	2,000	0.400	436	91.3	0.982	+179	--	--
10	3,000	160	0.625	118	21.6	0.956	+178	--	--
27.12	1,106	113	0.612	68.1	14.3	0.925	+177	0.651	-11.13
40.68	738	97.3	0.693	51.3	11.2	0.913	+176	0.652	-10.21
100	300	71.7	0.889	27	6.66	0.881	+175	0.650	-7.96
200	150	56.5	1.28	16.6	4.79	0.844	+175	0.612	-8.06
300	100	54	1.37	11.9	3.89	0.825	+175	0.592	-8.14
433	69.3	53	1.43	8.76	3.57	0.803	+175	0.562	-7.06
750	40	52	1.54	5.34	3.18	0.779	+176	0.532	-5.69
915	32.8	51	1.60	4.46	3.04	0.772	+177	0.519	-4.32
1500	20	49	1.77	2.81	2.42	0.761	+177	0.506	-3.66
2450	12.2	47	2.21	1.76	1.70	0.754	+177	0.500	-3.88
3000	10	46	2.26	1.45	1.61	0.751	+178	0.495	-3.20
5000	6	44	3.92	0.89	0.788	0.749	+177	0.502	-4.05
5800	5.17	43.3	4.73	0.775	0.720	0.746	+177	0.502	-4.29
8000	3.75	40	7.65	0.578	0.413	0.744	+176	0.513	-6.65
10000	3	39.9	10.3	0.464	0.343	0.743	+176	0.518	-5.95

* From Johnson and Guy [22].

TABLE II Properties of Microwaves in Biological Media*

		Fat, Bone, and Tissues with Low Water Content							
Frequency (MHz)	Wavelength In Air (cm)	Dielectric Constant (ϵ_L)	Conductivity σ_L (mmho/m)	Wavelength λ_L (cm)	Depth of Penetration (cm)	Reflection Coefficient Air-Fat Interface r	φ	Reflection Coefficient Fat-Muscle Interface r	φ
1	30,000	--	--	--	--	--	--	--	--
10	3,000	--	--	--	--	--	--	--	--
27.12	1,106	20	10.9 - 43.2	241	159	0.660	+174	0.651	+169
40.68	738	14.6	12.6 - 52.8	187	118	0.617	+173	0.652	+170
100	300	7.45	19.1 - 75.9	106	60.4	0.511	+168	0.650	+172
200	150	5.95	25.8 - 94.2	59.7	39.2	0.458	+168	0.612	+172
300	100	5.7	31.6 - 107	41	32.1	0.438	+169	0.592	+172
433	69.3	5.6	37.9 - 118	28.8	26.2	0.427	+170	0.562	+173
750	40	5.6	49.8 - 138	16.8	23	0.415	+173	0.532	+174
915	32.8	5.6	55.6 - 147	13.7	17.7	0.417	+173	0.519	+176
1500	20	5.6	70.8 - 171	8.41	13.9	0.412	+174	0.506	+176
2450	12.2	5.5	96.4 - 213	5.21	11.2	0.406	+176	0.500	+176
3000	10	5.5	110 - 234	4.25	9.74	0.406	+176	0.495	+177
5000	6	5.5	162 - 309	2.63	6.67	0.393	+176	0.502	+175
5800	5.17	5.05	186 - 338	2.29	5.24	0.388	+176	0.502	+176
8000	3.75	4.7	255 - 431	1.73	4.61	0.371	+176	0.513	+173
10000	3	4.5	324 - 549	1.41	3.39	0.363	+175	0.518	+174

* From Johnson and Guy [22].

TABLE III THERMAL AND PHYSICAL PROPERTIES OF HUMAN TISSUES *

Tissue	Sub-script	Specific Heat c Kcal/kg	Density ρ gm/cc	Metabolic Rate (W_o) W/kg	Blood flow Rate (m) ml/100 gm·min	Thermal Conductivity k mW/cm·°C
skeletal muscle (excised)	m		1.07			4.4
skeletal muscle (living)	m	.83		0.7	2.7	6.42
fat	f	.54	0.937			2.1[1]
bone(cortical)	bc	.3	1.79			14.6[1]
bone(spongy)	bs	.71	1.25			
blood	bl	.93	1.06[2]			5.06
heart muscle	m			33	84	
brain(excised)	br					5.0
brain(living)	br			11	54	8.05
kidney	k			20	420	
liver	l			6.7	57.7	
skin(excised)	s					2.5
skin(living)	s			1	12.8	4.42
whole body				1.3	8.6	

(1) For pig
(2) For human
*From Guy et al [22].

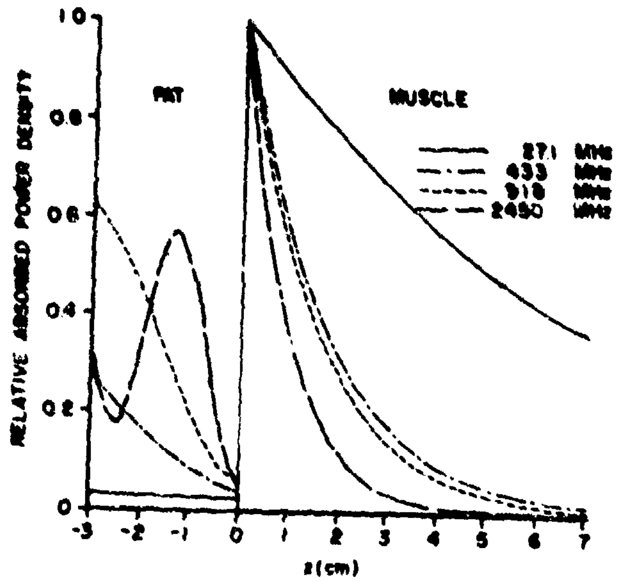


Fig. 1 Relative absorbed power density patterns in plane fat and muscle layers exposed to a plane wave source. From Johnson & Guy [22]

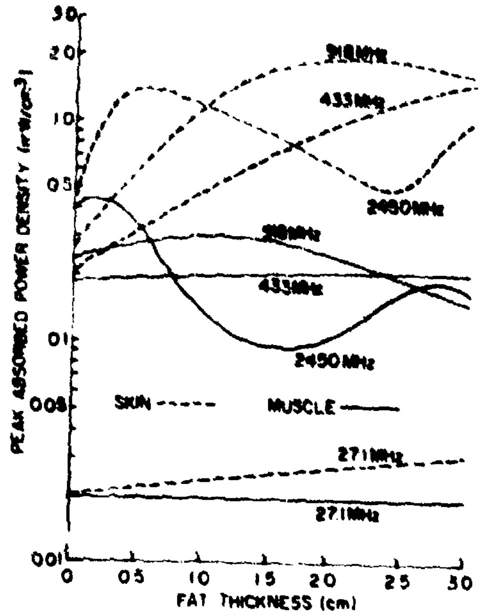


Fig. 2 Peak absorbed power density in plane skin and muscle layers as a function of fat thickness. From Johnson & Guy [22]

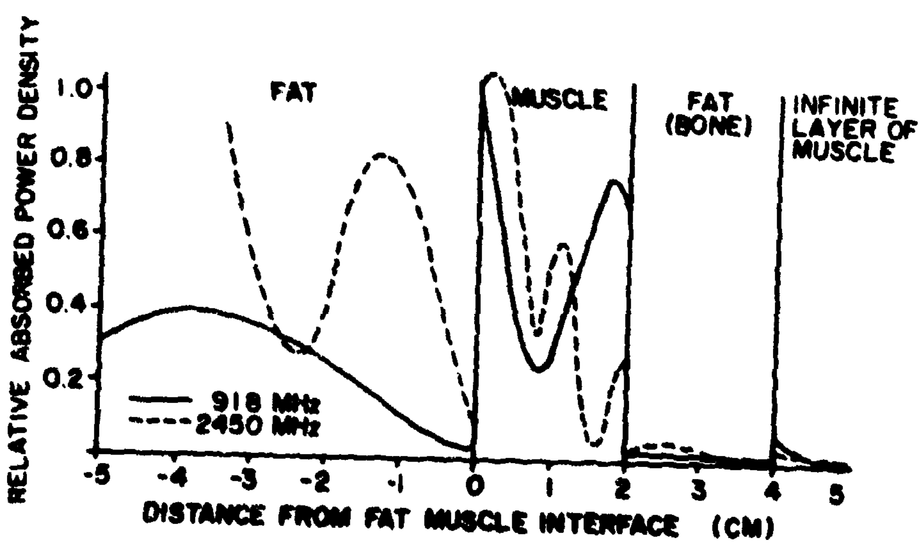
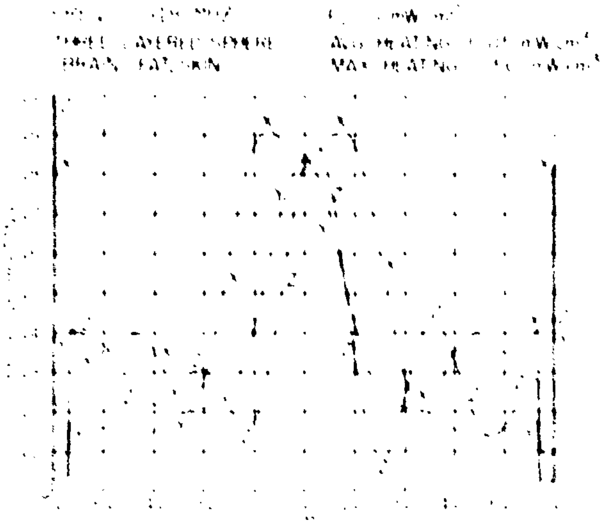
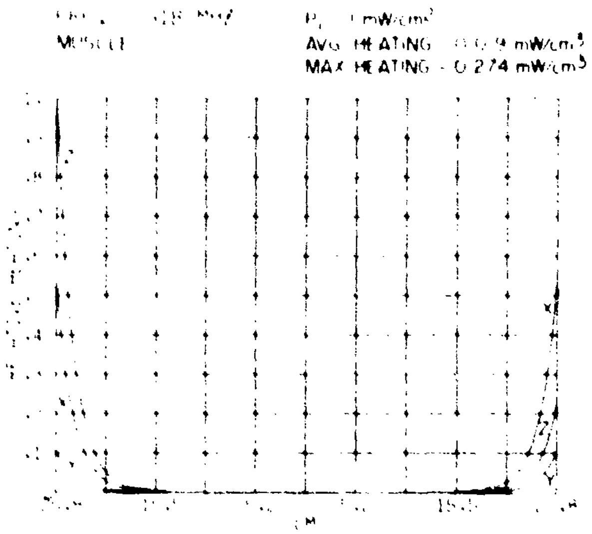


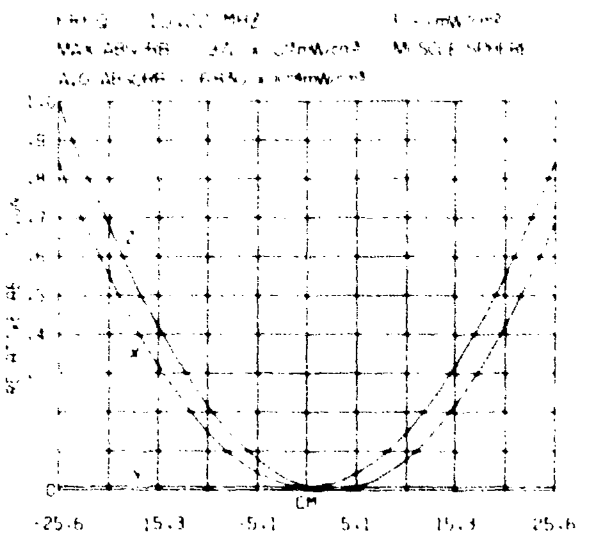
Fig. 3 Relative absorbed power density patterns in plane fat, muscle, and bone layers exposed to a plane wave source. From Johnson & Guy [22]



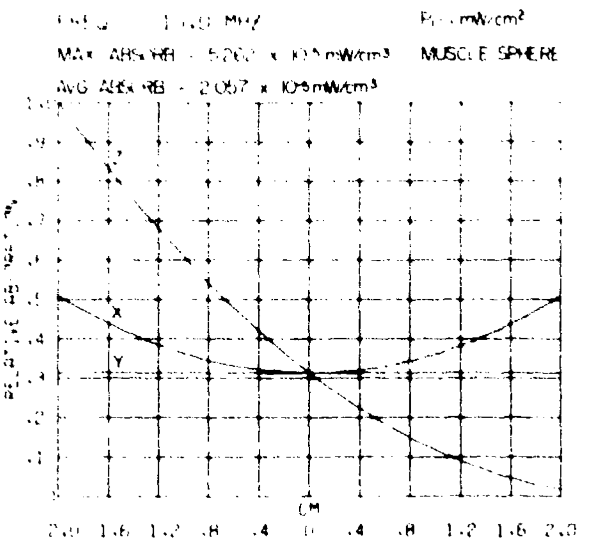
(a) Spherical model of human head with brain core surrounded by thin layers of bone and skin exposed to 918 MHz radiation (radius in the order of a wavelength in tissue).



(b) Spherical homogeneous muscle model simulating man exposed to 918 MHz radiation (radius large compared with a wavelength with tissue).



(c) Spherical homogeneous muscle model simulating man exposed to 10 MHz radiation (radius small compared with a wavelength in tissue).



(d) Spherical homogeneous muscle model simulating a mouse exposed to 10 MHz radiation (radius small compared with a wavelength in tissue).

Fig. 4 Power absorption densities in spherical tissue layers exposed to 1 mW/cm^2 incident plane wave power density. From Guy [23]

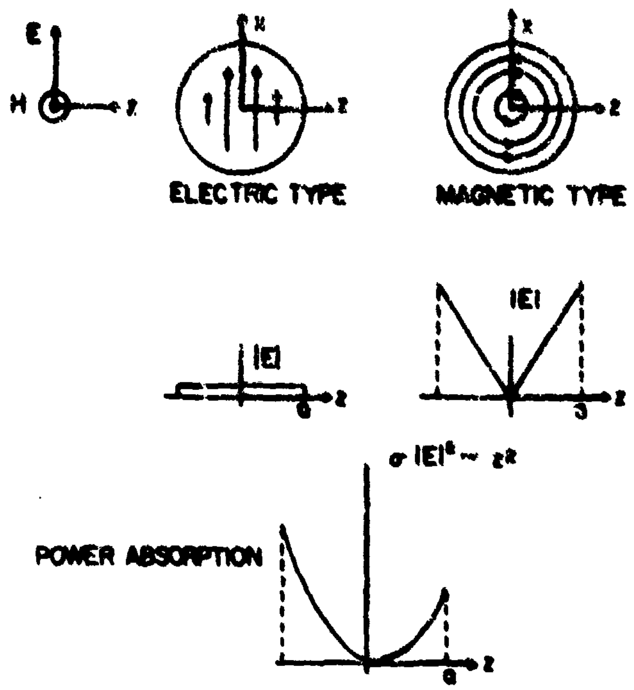


Fig. 5 Sketch depicting how electric and magnetically induced electric fields add in exposed tissue sphere ot produce absorbed distribution pattern. From Guy [23]

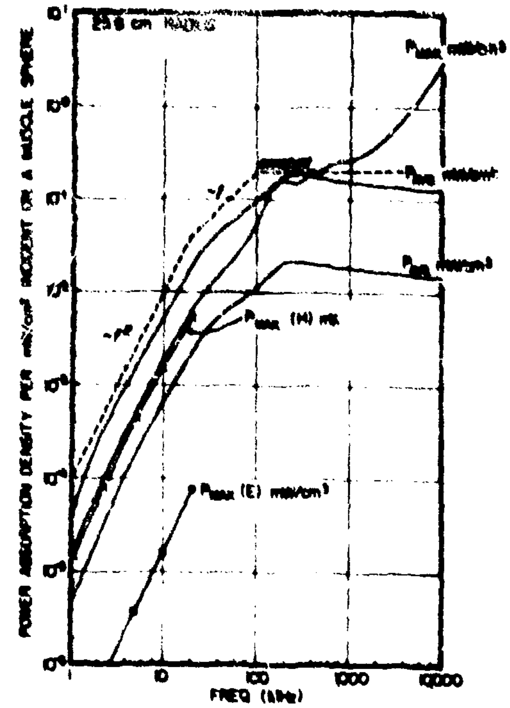


Fig. 6 Power absorption density patterns versus frequency in spherical muscle model of 70 kg man exposed to plane wave 1 mW/cm^2 source. From Guy [23]

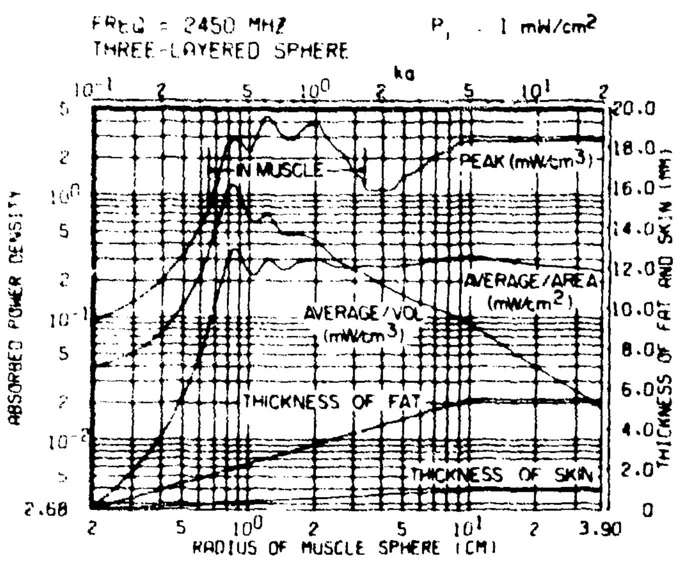


Fig. 7 Power absorption density versus outside radius in spherical tissue layer model of animal exposed to 2450 MHz 1 mW/cm^2 plane wave. From Guy [23]

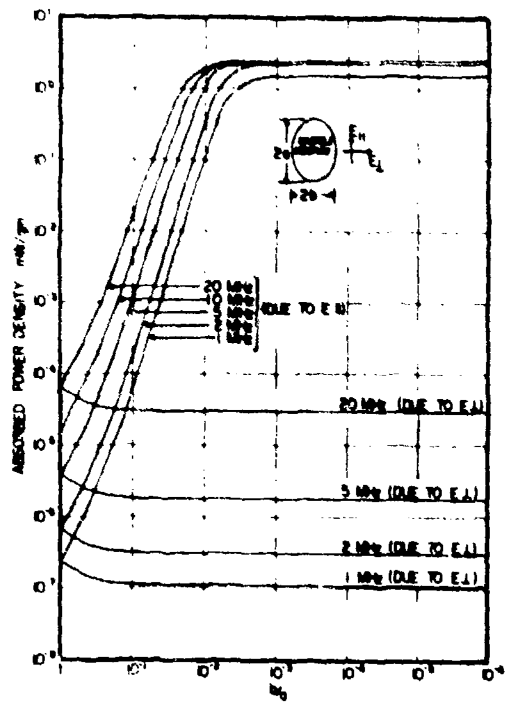


Fig. 8 Quasi-static solution of absorbed power density in prolate ellipsoid muscle medium exposed to 1 mW/cm^2 radiation field.

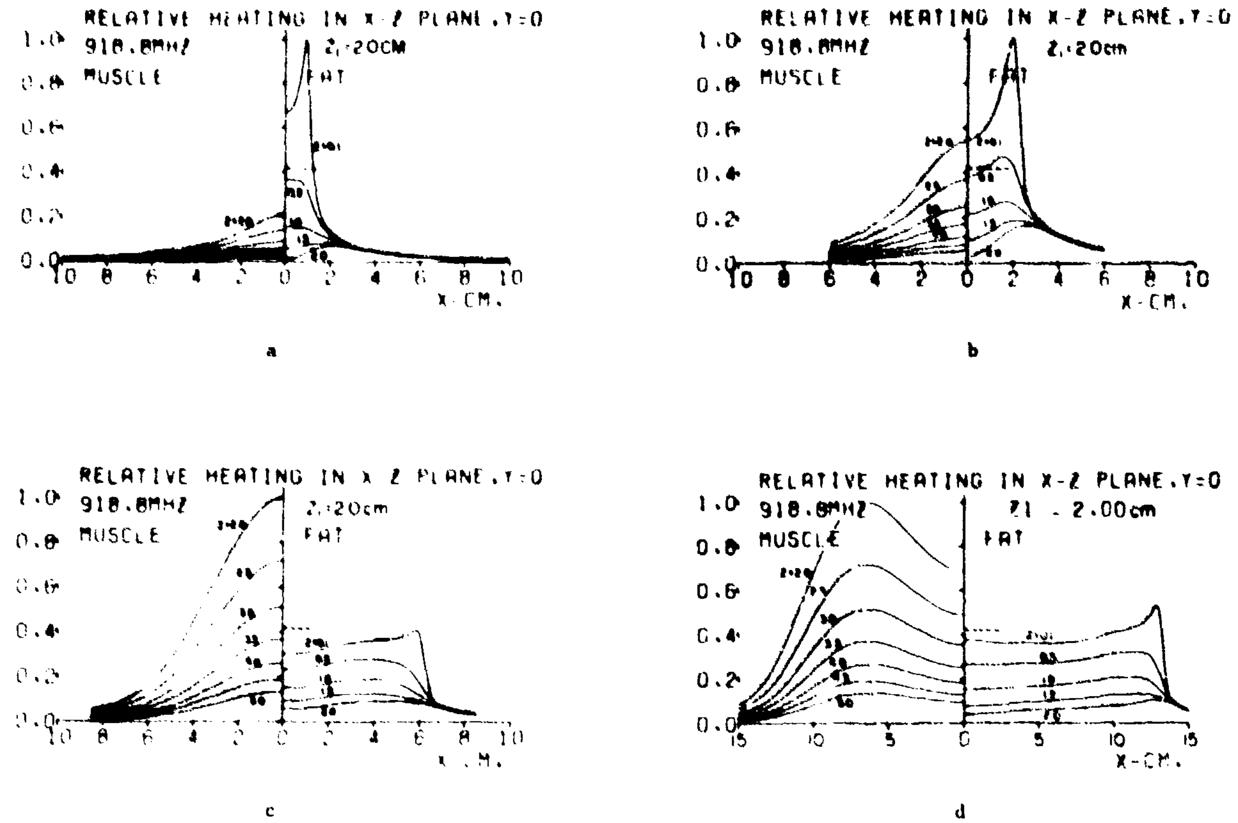


Fig. 9 Relative absorbed power density patterns in plane layers of fat and muscle exposed to TE_{10} mode waveguide aperture source with a = 12 cm, f = 918.8 MHz, and z_1 = 2 cm for various aperture heights. For (a) - (d) the values of b are 2, 4, 12, 26 cm, respectively. From Johnson & Guy [22]

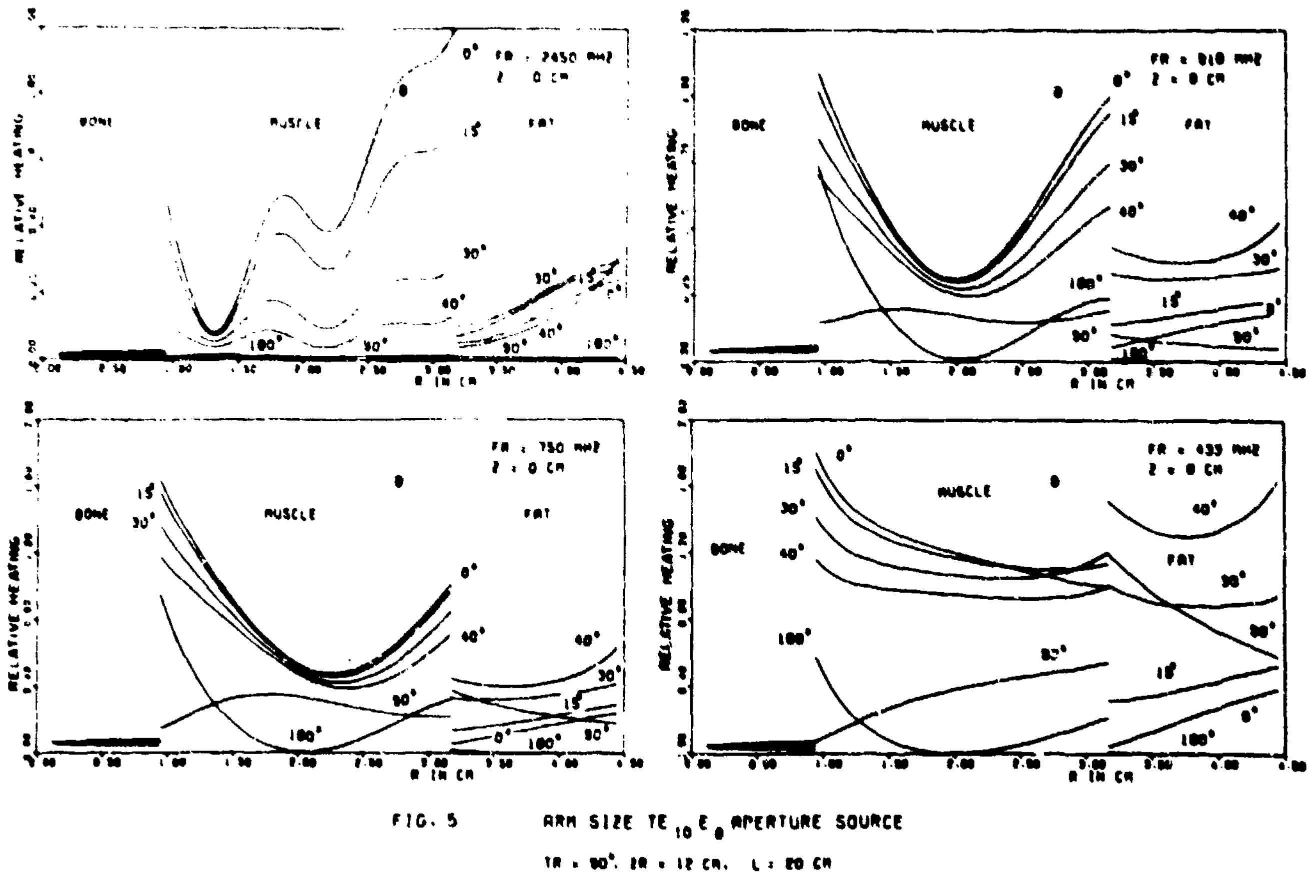


Fig. 10 Heating patterns in a cylindrical model of human arm due to a direct contact cylindrical aperture source. From Johnson & Guy [22]

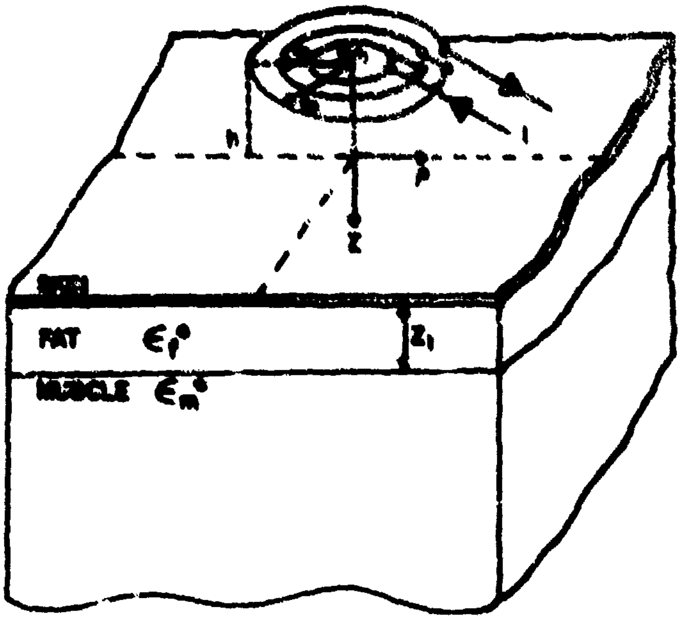


Fig. 11 Geometry and coordinates for a skin-fat-muscle tissue geometry exposed to a flat "pancake" diathermy induction coil. From Guy, et al. [21]

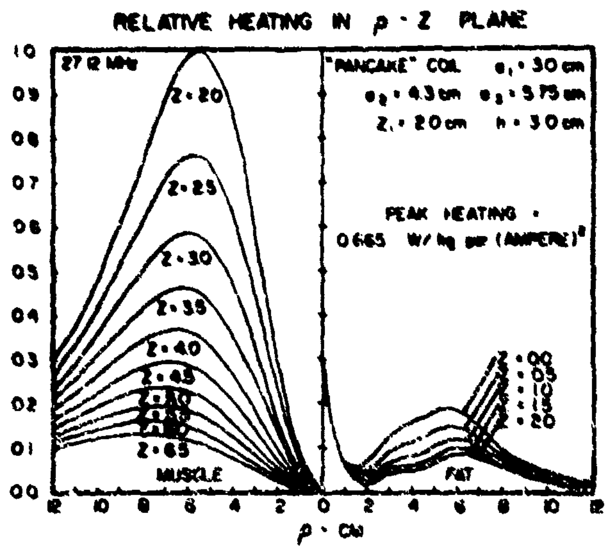


Fig. 12 Calculated absorbed power patterns in planar fat and muscle tissue layers exposed to shortwave diathermy induction coil. From Guy, et al. [21]

ELECTROMAGNETIC RADIATION EFFECTS ON THE EYE

by

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SUMMARY

Studies of the biological effects of electromagnetic radiation (EMR) exposure often cite lens opacification as a major threat to man. The purpose of this paper is to analyze, collectively, the EMR research studies on ocular effects and provide an overview of the practical aspects of this problem today. The principal conclusions from this effort are: (1) The acute thermal insult from high intensity EMR fields is cataractogenic if intraocular temperatures reach 45-55° C. (2) The EMR exposure threshold is about 100-150 mW/cm² applied for about 60-100 minutes. (3) There does not appear to be a cumulative effect from EMR exposures unless each single exposure is sufficient to produce some irreparable degree of injury to the eye.

INTRODUCTION

The fact that microwaves can produce lenticular opacities of the eye has been known for over two decades (1-6). In any general assessment of the biological effects of electromagnetic radiation fields, the eye is often identified as the critical organ of concern. However, the bulk of available experimental evidence (7-10) supports the position that electromagnetic (microwave/radiofrequency) radiation (EMR) exposures greater than 100 mW/cm² for periods longer than an hour are required to produce lens opacification. Validation and acceptance of this threshold value for EMR cataractogenesis have a profound effect on future research needs to assess the consequences of man's exposure in EMR fields.

EVIDENCE OF EMR CATARACTOGENESIS

Numerous experiments have been conducted to determine the EMR thresholds for production of lenticular opacities as a function of frequency, power density, and exposure time. Extensive reviews of such data are reported in the open literature (7, 8, 11). The following table provides a summary of research findings and conclusions of representative studies.

SUMMARY OF EXPERIMENTAL EVIDENCE OF EMR CATARACTOGENESIS

Refs	Investigator/ Author, Date	Freq. (MHz)	Animal	Exposure Profile	Results/Conclusions
2	Richardson A.W., 1948	2,400 10,000	Rabbits	100 W output, eyes 5 cm from source, temp at posterior pole of lens as high as 55° C.	32 of 54 irradiated eyes developed lenticular opacities. Concluded - thermal effect.
3	Osborne, S.L., 1948	2,450	Dogs	Eyes exposed to 350-450 mW/cm² for 20 min per exposure over 3-week period.	No evidence of damage to the eyes.
5, 6	Daily, L., 1950-1952	2,450	Dogs Rabbits	100 W output, intraocular temp rise 3° C in dogs. Repeated exposures with 2-5 inches space between "C" director and cornea for 10-30 minutes.	Anterior cortical cataracts developed in 24 hrs and regressed over 9 wks. Posterior cortical cataracts developed over 9 wks. Under same exposure conditions for rabbits, 7 of 17 albino and 3 of 17 pigmented rabbits developed cataracts.
				6-10 exposures of the eyes of dogs to 300 mW/cm² for 30 min.	Failed to show any ocular damage.

SUMMARY (Continued)

Refs	Investigator/ Author, Date	Freq. (MHz)	Animal	Exposure Profile	Results/Conclusions
4	Richardson A. W., 1951	10,000	Rabbits	34-67 W output, pulsed exposures, 3-5 min, at 5 cm distance.	16 of 21 rabbits developed opacities within 60 days.
12, 13	Williams, D. B., 1955	2,450	Rabbits	5 min at 590 mW/cm^2 to 90 min at 290 mW/cm^2. Intraocular temps. 49-53° C.	Cataracts developed over 1-14 day latent period. Threshold ~120 mW/cm^2.
8, 14	Addington, C. H., 1958-1959	200	Guinea pigs Dogs Mice	Free space exposures of 50 to 350 mW/cm^2, 60 min/day; 3, 5, or 7 day/wk or continuously for periods up to 45 wks. Average increase in rectal temp < 2° F.	No evidence of lens change could be found
8, 15	Cogan, D. G., 1958	400	Rabbits	60 mW/cm^2 within wave-guide and in free space	No cataracts produced with whole body exposures near lethal levels.
7, 8	Carpenter, R. L., 1958-1960, 1968, 1972	2,450	Rabbits	50 mW/cm^2 to 120 mW/cm^2, 1 hr/day for 20 consecutive days. Continuous (CW) and Pulsed (P).	Cataract threshold ≈ 120 mW/cm^2 for cumulative exposures, 1-6 day latent period for appearance of cataracts. CW vs P exposures inconclusive.
23	Reider, D. R., 1971	20	Primates	Four rhesus monkeys exposed to pulsed fields 180 mW/cm^2 for 4 hours.	Eye examination 1, 4, & 7 days postexposure and weekly for 8 weeks revealed no ocular change.
16	Birenbaum, L., 1969	3,500 (800 - 6,300)	Rabbits	100 exposures to pulsed fields. 62 exposures to CW fields.	Thresholds for cataracts similar to Carpenter data (~120 mW/cm^2), latent period 4 days. No detectable difference between P and CW exposures. Effectiveness of radiation diminished with decreasing frequency.
8	Baillie, H. D., 1969	2,500	Dogs	5000 mW/cm^2 exposures under hypothermic conditions (cooled to 22° C).	Without cooling, immediate and delayed cataracts were produced. Under hypothermic conditions no cataracts were produced even with repeated exposures. Concluded - Cataract production is thermal effect.
7, 8	Michaelson, S. M., 1961-1974	2,800	Rabbits	Free space exposures 220-240 mW/cm^2 for one hour.	Produced rapid and complete opacification (also profound thermal effects were observed).
		2,800	Dogs	Pulsed exposures at 165 mW/cm^2 for 3 hrs in a single exposure or 6 hr/day for 3 wks.	Did not produce any lenticular changes for several years after irradiation.
		1,280	Dogs	Pulsed fields at 20, 50, or 100 mW/cm^2, 6 hr/day, 5 days/wk, 2-4 wks.	Periodic examination for 12 months after exposures did not reveal abnormalities of the lens or retina.

SUMMARY (Continued)

Refs	Investigator/ Author, Date	Freq. (MHz)	Animal	Exposure Profile	Results/Conclusions
7, 8	Michaelson, S. M., 1961-1974	24,000	Dogs	Pulsed fields, ~ 6 hr/day, 5 days/wk, or ~16 hr/day, 4 days/wk, for 20 months. (In these exposures the dogs were free to move around.)	No eye abnormalities in lens or retina.
		2,800	Dogs	Single or fractionated exposures to 350 mW/cm^2 for 20 min.	No permanent lenticular alterations.
				Single or fractionated exposures to 700 mW/cm^2 for 20 min.	Resulted in lens opacification.
9, 10	Guy, A. W., 1974 Kramar, P. O., 1975	2,450	Rabbits	Exposure levels from ~100 mW/cm^2 to 500 mW/cm^2 for 10-100 minutes.	Exposure threshold for cataract production was 150 mW/cm^2 for 100 min. Data suggest critical temperature for cataractogenesis is ~43° C.
		2,450	Rabbits	Exposed to same exposure levels under hypothermic conditions.	Concluded that single potentially cataractogenic exposures will not injure the eye under conditions of controlled general hypothermia. Conclusion - Heat alone is responsible for damage to the lens following single, high-level irradiation.
		2,450	Rabbits	Exposure levels - 100 mW/cm^2, 30 min/day, 4 days; 100 mW/cm^2, 60 min/day, 5-9 days; 100 mW/cm^2, 120 min/day, 8-9 days.	Periodic exams for six months after exposure revealed no ocular damage.
		918	Rabbits	Exposure 1400 mW/cm^2 for 30 min.	Concluded threshold for cataractogenesis is higher for this frequency when compared to 2450.
24	Williams, R. J., 1974	2,450 2,860	Rabbits	Multiple exposure CW and pulsed, 225 mW/cm^2, 20-30 min daily for up to 5 weeks.	Radiation did not appear to influence the normal cornea. No detectable effect.
21	Appleton, B. 1975	3,000	Rabbits	100 or 200 mW/cm^2 for 15 or 30 min.	Examination daily for 14 days, weekly for one month, and monthly for a year revealed no ocular changes.
				300, 400, or 500 mW/cm^2 for 15 min.	Acute ocular changes during exposure. Animal deaths occurred after 30 min @ 300 mW/cm^2 and 15 min @ 500 mW/cm^2. No lens changes or cataracts were noted at one year postexposure.

SUMMARY (Continued)

Refs	Investigator Author, Date	Freq. (MHz)	Animal	Exposure Profile	Results/Conclusions
26	Williams, R.J., 1975	2,450	Rabbits	250 mW/cm^2, 20 min/day, 5 day/wk for 6 wks. 165 mW/cm^2, 20 min - 2 times daily, 5 day/wk, for 3 wks.	Electron microscopy revealed prominent ultrastructural changes in one lens that had appeared normal by slit lamp biomicroscopy.

The fact that these studies were conducted over a span of 25 years poses some difficulty in comparing the research results and conclusions, particularly considering the lack of quantitative dosimetry in some of the earlier investigations. However, taken collectively, they reveal certain consistencies which must be considered in an analysis of EMR cataractogenesis. The acute thermal insult appears as a primary mechanism for producing eye trauma leading to lens opacities, but is effective only above some power density-time threshold. These studies indicate this threshold value is greater than 100 mW/cm^2 applied for more than an hour. Although most of the experimental work has been conducted using 2450 MHz radiation sources, the data suggest that lower frequencies require more intense radiation exposures to produce comparable lenticular damage. This is logical from the standpoint of thermal insult since EMR energy transfer to biological tissue is frequency dependent, with the higher frequencies producing the maximum energy density.

The studies conducted under hypothermic conditions provide remarkably strong evidence that heat alone is responsible for ocular lens damage following single high-intensity EMR exposures. Thus, time of exposure is also a critical parameter for lens injury.

In studies where the radiation was applied to the whole body of the animal, lethality often resulted. In a practical sense, this should reduce the concern for acute eye injuries from EMR exposures. Studies such as these cause questions to be raised concerning the selection of test subjects and extrapolation of the research findings to man. However, it is believed that the EMR exposures used in these experiments represent a worst case biological insult, i.e., these exposures were more traumatic to the animals than they would be to man.

Many different types of retrospective studies have been conducted in an attempt to gain useful data from actual or suspected exposure of human populations to EMR fields. One of the earliest of such studies was performed in 1943 (7, 8, 17) on 45 military radar operators. In 1958, another study of 335 microwave workers was reported (7, 8, 18). Neither survey revealed any significant findings. A more extensive but different type of study (7, 8, 19) of the records of 2,946 World War II and Korean veterans treated by the U.S. Veterans Administration Hospitals for cataracts compared to those of 2,164 veterans without cataracts was made to determine if the cataract incidence could be related to greater occupational risk (exposure to EMR). It was concluded that the group occupationally exposed or associated with microwaves exhibited no increased risks of cataracts. References 7 and 8 discuss, in detail, the major controversies concerning the interpretation and validity of a number of occupational surveys and individual case reports.

In spite of repeated attempts to analyze and apply data from retrospective studies, little has been gained from such efforts. However, the following general observations are worthy of consideration:

(1) Human data alone does not provide conclusive evidence that EMR produces cataracts in man.

(2) Some surveys may indicate statistically significant increases in lenticular defects in microwave workers, but none has shown any clinically significant defects in terms of decreased visual acuity, i.e., no apparent loss of functional vision.

(3) Case reports of diathermy treatment in the area of the eye using multiple exposures at power densities of 80-240 mW/cm^2 did not result in production of cataracts.

(4) The exposure levels with which clinically significant cataracts have been tenuously associated indicate the cataractogenic threshold is over 100 mW/cm^2 for man.

(5) Human populations, including groups that work with or near EMR emitters, are rarely subjected to fields having average power densities greater than about 1 mW/cm^2 and in most cases the fields are lower.

DISCUSSION

Interpretation and significance of controlled research studies and retrospective surveys of various population groups will be debated for many years to come. The controversies will include applicability of specific laboratory procedures used to administer and measure EMR fields and the tools and

techniques used to quantitate biological response. The current state-of-knowledge concerning EMR effects on the eye may be summarized briefly as follows:

The acute thermal insult resulting from EMR exposures is believed to be the predominant mechanism responsible for the production of lenticular opacities in the eye (7, 9). It appears that intraocular temperatures in the range of ~45-55°C must be reached before opacities develop. Thus, cumulative effects of EMR exposures would not be anticipated unless each single exposure exceeded the critical threshold level necessary to produce some degree of irreparable injury. Based on the experimental evidence summarized herein, the threshold level is greater than 100 mW/cm² applied for more than one hour. A latency period of several days is indicated for the development of cataracts. Additionally, Michaelson reports (7), "No one has yet been able to produce cataracts even by repetitive exposures when the power density is really below threshold." Appleton, who has been actively engaged in clinical surveys of numerous military population groups (20) and microwave research studies (21), further states: "1. Lens damage probably has not occurred in humans from cumulative exposure to low levels of microwave energy. 2. Lens damage probably could not occur in a human from acute exposure to microwave energy without associated severe facial burns." (22).

While the emphasis in past research studies and in this paper is on acute EMR cataractogenesis, future studies of the effect of EMR on the eye should consider more subtle indications of energy transfer, such as alterations in lens protein and/or ultrastructural changes, and any possible long-term adverse consequences (25, 26).

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Endocrine and Central Nervous System Effects of Microwave Exposure

by

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Functional alterations in the neuroendocrine system of both animals and humans exposed to microwaves have been reported by several investigators. The findings include changes in the secretions of the pituitary gland, adrenal cortex, thyroid gland, and the gonads. In most cases, the endocrine changes attributed to microwave exposure have not been adequately documented. The findings of a large number of studies have been used to overstate the conclusions, or derive assumptions incompatible with the cybernetic model of the function of the neuroendocrine system. Conflicting and inconsistent results of research and observations by various investigators also exist (1).

Some investigators believe endocrine changes result from stimulation of the hypothalamic-hypophysial system due to thermal interactions at the hypothalamic or immediately adjacent levels of organization, the hypophysis itself (pituitary), or the particular endocrine gland or end-organ under study. According to other investigators, the observed changes have been interpreted as being the result of direct microwave interactions with the central nervous system.

HYPOTHALAMIC-HYPOPHYSIAL-ADRENAL RESPONSE

Several investigators have reported biochemical and physiological changes as a result of microwave exposure which suggest an adrenal effect. Three and 24 hours after dogs were irradiated with 3000 MHz, 10 mW/cm^2, the corticosteroid content in their blood increased by 100 and 150% above the original level, while blood potassium was down 5-10% and blood sodium up by percentages in the same range (2). Susceptibility of rats to microwave exposure was sharply increased 1 week after bilateral adrenalectomy (2).

The pituitary gland in female mice exposed to 3000 MHz (10 mW/cm^2) twice daily for 5 months, preserved its gonadotropic function, although its activity was reduced in comparison with that in nonexposed animals (3). Tolgskaya and Gordon (4), in discussing the dynamics of changes in the neurosecretory function of the hypothalamus noted the reversibility of the process when exposure is terminated.

In rats exposed to microwaves of varying intensity, no quantitative changes in corticosterone were found in the adrenals and blood plasma. Prepubescent rats with the pituitary removed displayed no differences in adrenal growth rate when treated with pituitary homogenates collected from rats exposed to microwaves as well as from control rats (1). Rats exposed to 2 [illegible] MHz (CW), 10 mW/cm^2 for 4 hours, showed no change in adrenal weights, phenylethanolamine-N-methyl transferase (PNMT) activity or epinephrine levels (5). After 16 hours of exposure (0.4°C increase in rectal temperature compared to controls), however, decrease in adrenal epinephrine (32%) was significant and PNMT activity was elevated 25%. There were no statistically significant differences ($p > 0.1$) between exposed and sham-exposed animals in adrenal or plasma corticosterone levels. In agreement with these findings, no significant changes were noted in numbers of circulating lymphocytes or eosinophils. The author suggested that although eosinophil and lymphocyte counts, as well as direct measurements of adrenal and plasma corticosterone failed to document a pituitary-adrenal response, the decreased adrenal epinephrine levels and elevated PNMT activity probably indicate adrenal epinephrine release and by compensation, augmented epinephrine synthesis via sympathetic nervous system stimulation. It should be noted, however, that similar alterations in epinephrine levels have been noted to occur in rats subjected to a stressful situation, such as immobilization or acute exposure to cold.

Petrov and Syngayevskaya (2) suggest that the enhancement of corticosteroid activity during and after irradiation could be an adaptive reaction. Some animals develop inhibition of adrenal-cortical function (corticosteroid activity), attended by a decline in resistance to microwaves reflecting insufficient ACTH. Increased resistance may be related to an increase in the secretion of ACTH, which would also be an adaptive reaction of the organism. This is supported by the finding that the resistance of some animals to microwaves is slightly increased when ACTH is administered.

HYPOTHALAMIC-HYPOPHYSIAL-THYROID RESPONSE

The literature offers comparatively few experimental studies of the effect of microwaves on the thyroid. Rats exposed to various regimens of microwave radiation (2450 MHz, CW, 1 mW/cm^2 continuously for 8 weeks or 10 mW/cm^2, 8 hr/day for 8 weeks) were evaluated in terms of their thyroid and thyrotropic activity. No alterations in structure or function were noted which could be attributed to a specific effect of microwave radiation (6). On the other hand, a stimulatory influence of 5 mW/cm^2 on the trapping and secretory functions of the thyroid gland of rabbits has been reported (7). These functional changes were in agreement with altered histology of the thyroids.

The ability of the thyroid to concentrate iodide, as measured by the ratio of accumulated thyroidal ^{131}I divided by the concentration of serum ^{131}I, T/S (I^-), was reduced in rats exposed for 16 hours to 2450 MHz (CW) at field intensities of 20 and 25 mW/cm^2, but the reductions were not statistically significant (5). In these animals there was a 1.0°C-1.7°C increase in rectal temperature relative to controls. Serum protein-bound iodine (PBI) and thyroxine levels were slightly but not significantly decreased at 10, 15, and 25 mW/cm^2 after 16 hours of irradiation ($p > 0.05$). Exposure at an intensity of 15 mW/cm^2 for 60 hours produced a decrease in PBI of 23%, and a decrease in serum thyroxine of 55%, both of which were statistically significant at the 0.05 and 0.005 confidence levels, respectively. Results of rectal temperature measurements after 16 or 60 hours demonstrated only a slight and statistically insignificant temperature rise up to a field intensity of 20 mW/cm^2. Above this level, the rectal temperature increased sharply (5). The author suggests that these results could be due to a primary effect on the thyroid, the pituitary, the hypothalamus, or any combination of these. Although the temperature increase was not marked, the author does note that at this exposure level (15 mW/cm^2) there was a 0.5°C ± 0.3 (SEM) rise in rectal temperature after a 60 hour exposure.

Indirect evidence has been obtained of some protective influence of lowered general and tissue metabolic rate following hypophysectomy on the time-related lethal exposure of rats to microwaves (8). The survival

time of normal rats exposed to microwaves was largely a function of body mass; survival time per unit of body weight was significantly longer in hypophysectomized than in normal rats.

Increased radioactive iodine uptake (RAIU) has been observed in dogs exposed to 1280 or 2880 MHz pulsed microwaves, 100-165 mW/cm² (9). This was felt to be a result of increased thyroid stimulating hormone (TSH) due to thermal stimulation of hypothalamic-hypophysial activity. The microwave effect on thyroid response was transient since repeated thyroid ^{131}I uptake studies revealed a return in ^{131}I uptake values to normal levels. After daily microwave exposure of 1 to 5 weeks duration at 20 or 50 mW/cm², some dogs had an increase in ^{131}I uptake. The relationship of ^{131}I uptake to elapsed time following 20 and 50 mW/cm² was ill-defined, whereas following a single 100 mW/cm² exposure the ^{131}I uptake indicated a time-related effect.

It has been reported that microwave exposed workers have developed enlargement of the thyroid gland as well as an increased RAIU, but in some cases without clinical symptoms of hyperfunction (10). It was not possible, however, to establish correlation between the amount of thyroid activation and each individual's microwave exposure history. Because of inadequate controls, inappropriate control matching, and other reasons, the data as presented could as easily represent the normal incidence of these particular clinical findings in this particular occupational population.

D'Yachenko (11) described the results of a study of thyroid function in 38 men,24 to 39 years old,who operated microwave equipment (centimeter band) for 3 to 15 years. An "asthenic-neurosis" syndrome was found in 18 of the subjects, while an enhanced 2-24 hour ^{131}I uptake by the thyroid was found in all of the individuals. The changes in thyroid function in these subjects is attributed by the author to secondary effects resulting from radiation-induced disturbances of the sympathetic nervous system in the vicinity of the hypothalamus.

Clinical studies and functional investigations of the thyroid by T4 and T3 determinations in 142 men servicing microwave equipment at power density exposures of 10 µW-1 mW/cm² did not reveal significant disturbances in thyroid function (12). A difference between the mean values of T4 and basal metabolism in the control group compared with the subjects exposed to microwaves was attributed by the investigators to extraneous effects, i.e. hypersensitivity of the central nervous system, since neurovegetative disorders were found in 61-72 percent of persons exposed to microwaves; cause-effect relationship was not established.

Subbota (13) reviewed the influence of low "nonthermal" intensity microwave radiation on the organism. Although he did not specifically discuss thyroid or other neuroendocrine changes in experimental animals at low levels, he did state, however, "it may be assumed that a change in the normal activity of the central nervous system is the primary link in the various functional disturbances, and that endocrine gland activity changes are secondary. On the other hand, derangement of cardiovascular, gastric, and other functions is a consequence of disturbed neuroendocrine regulation."

Petrov (14) discussed the influence of microwave radiation at high (thermal) intensities on the thyroid gland in experimental animals, indicating that enhanced thyroid function has generally been noted. He concluded that "disturbances to neurohumoral regulation appear under irradiation with high-intensity microwaves that cause an increase in body temperature, owing to changes in the functions of the CNS and certain endocrine glands." McLees and Finch (15) have reviewed the experimental animal data which indicate an increased RAIU by the thyroid following microwave exposure. They also point out that temperature elevation and heat stress have been associated with alterations in radioactive iodine turnover rate.

In trying to assess the effect of microwave exposure on the thyroid gland, one is led to the conclusion that perturbation of this endocrine organ may be the result of an indirect effect; the thermal stress on the body producing an hypothalamic-hypophysial response. This is consistent with microwave induced thermal stimulation of hypothalamic-hypophysial-thyroid (HHT) activity (16). These changes in thyroid activity could be the result of increased thyroid stimulating hormone (TSH) and/or increased metabolic activity of the thyroid gland due to heating. Since thyroid gland activity has been shown to be altered by both sympathetic and parasympathetic nerve stimulation (17), the above changes could also be the result of some direct interaction of microwaves on the central nervous system. The HHT axis, however, has been shown to be critically sensitive to environmental temperature (18). Thus, thyroid changes due to microwave exposure could be due to small changes in peripheral temperature.

EFFECTS ON THE NERVOUS SYSTEM

Transient functional changes referrable to the central nervous system have been reported following low-level (<10 mW/cm²) microwave irradiation. Eastern European investigators stress that the CNS is highly sensitive to all forms of radiation. Although some reports describe the thermal nature of microwaves, the majority stress nonthermal or specific microwave effects at the molecular and cellular level. It should be noted, however, that changes in nervous system function may not be specific (19), and a specific, e.g., nonthermal microwave effect has not been experimentally verified (20).

Animal experiments

In one of the earliest studies on neurologic effects of microwaves by Oldendorf (21), evidence was found of focal coagulation necrosis in rabbits brains exposed to 2450 MHz. The first report on the effect of microwave energy in the centimeter range on the conditional response activity of experimental animals was made by Gordon et al (22). In subsequent years, the study of the "nonthermal" effects of microwaves gradually occupied the central role in electrophysiological studies in the Soviet Union (23).

Baldwin et al (24) found that exposure of monkeys to 225-400 MHz was followed by signs of agitation, drowsiness, akinesia and eye signs, as well as autonomic, sensory, and motor abnormalities. There were signs of diencephalic and mesencephalic disturbances; alternation of arousal and drowsiness, together with confirming EEG signs. The response depended on orientation of the head in the field and reflections from the surrounding enclosure. Rabbits whose heads were exposed for 30 minutes to 3 to 300 MHz showed increased excitation of cortical and other visual analyzers (25).

Tolgskaya et al (26) studied the effects of pulsed and CW 3000 and 10,000 MHz microwaves on rats at various intensities. Emphasis was placed on morphologic changes. The more pronounced morphologic changes in the nervous system following 3000 MHz than 10,000 MHz at 1-10 mW/cm² was interpreted as evidence of a nonthermal effect. Pulsed waves were more effective than CW. The greater effectiveness of pulsed microwaves was also noted by Marha (27).

Conditional response (CR). Yakovleva and associates (28) reported that single and repeated exposures of rats to microwaves, 5-15 mW/cm², weakened the excitation process and decreased the functional activity of cells in the cerebral cortex. Edematous changes were most often noted throughout the entire cross-section of the cortex. The greatest number of altered cells was noted with repeated exposures at 15 mW/cm².

Lobanova (29) summarized her findings at 3000 MHz suggesting two phases are evident in changes in CR during exposure, an increase in excitability of the central nervous system, i.e. a weakening of active inhibition; and a second phase of weakened excitation, with the development of external inhibition. In a

later study, however, she reported that chronic exposure of animals to RF in the 155-191 MHz range for 4.5 months at "low intensity" does not have a marked effect on their CR (30).

Conditional response alteration has been reported in dogs exposed to SHF (3000-30,000 MHz) for 1-2 hours (31). The direction of changes in "intense" radiation was, in the majority of cases, opposite to that observed after "weak" radiation. At 5 mW/cm^2 increased salivation was observed as a positive CR with relative stability of differentiation; the latent period of CR in the majority of cases was shortened with 100 mW/cm^2. A positive CR was almost always depressed, and differentiations were delayed; tests with repeated radiation indicated the possible adaptation of the cortex to the EMF. In rabbits, brief exposure to 10 mW/cm^2 VHF (30-300 MHz) intensified conditional responses to different stimuli, whereas prolonged exposure produced an inhibitory effect. Selective sensitivity of the brain to this frequency was demonstrated by reversible structural changes in the cerebral cortex and in the diencephalon (32, 33).

It is apparent that Eastern European investigators have a great interest in conditional response phenomena. To understand their reports, one must read them in the context in which they are written, whether one accepts the precepts behind the writing or not. These investigators base much of their conceptual approach on Pavlovian conditional response techniques and interpretation. It should be mentioned in this context that an effect is observed only in experiments conducted according to the schemes used by I.P. Pavlov and his followers. Among investigators that have studied conditioned reflexes in different animals, there is disagreement in the evaluation of the observed phenomena and their mechanism (34).

Cortical effects. Several investigators have reported that microwave exposure produces alteration in the electroencephalogram (EEG) (32, 35, 36, 37). Stimulation is often followed by increased amplitude and decreased frequency of EEG components, or by decreased amplitude and increased frequency. The general character of the observed EEG alterations is constant throughout a wide range of intensities (.02 mW/cm^2 to ~ 100 mW/cm^2). In general, the percentage of cases evidencing alterations increases with increasing intensity. However, some investigators revealed a greater percent of responses at .02 mW/cm^2 than at intermediate intensities (37). The EEG responses show a substantial delay which decreases with radiation intensity from about 100 sec at .02 mW/cm^2 to about 20 sec at 10 mW/cm^2. Rabbits exposed to 10,000 MHz, pulsed, at 5 mW/cm^2 single exposure showed no changes in EEG tracings, but exposure to 3000 MHz, 7 mW/cm^2, 3 hours/day for 60 days produced functional changes (38).

Reviewing the literature on EEG effects requires awareness of certain deficiencies in this methodology. There is not always a one-to-one correspondence between functional state and character of EEG recording - which may lead to mistaken interpretation of the functional consequences of changes in the character of spontaneous activity as the result of exposure to microwaves. Spontaneous activity may be easy to measure, but extremely difficult to interpret (39).

Behavioral effects. Justesen and King (40) studied the behavioral effects in rats exposed in a closed space situation to 2450 MHz. Average power densities approximated 2.5, 5.0, 10 or 15 mW/cm^2. A major finding was rate of recurrence of an iterative (phasic) tongue-licking reflex. At the high level of 15 mW/cm^2, there invariably occurred a behavioral state suggesting flaccid paralysis. The animal recovered within 5-10 minutes after removal from the experimental chamber and thereafter exhibited no behavioral signs indicative of stress. Rectal temperature data confirmed an impression growing from earlier behavioral observations that the rat is highly variable in its thermoregulatory capability. No chronic ill effects, behaviorally or neurohistologically, were found after fairly long-term intermittent exposures at 2.5 to 15 mW/cm^2. Although some acute effects were observed, none was incompatible with the supposition that thermal input was the only consequence of irradiation.

Diachenko and Milroy (41) reported a study of pulsed and low-level CW microwave radiation effects on an operant beharior in rats. The subjects were trained to perform a lever pressing response on a DRL schedule (differential reinforcement of low rate) and tested immediately after one hour daily exposure for one week to 1, 5, 10, 15 mW/cm^2 power levels of 2450 MHz while other subjects were exposed to a pulsed field of 125 kV/m. No effects were found at the 1, 5, and 10 mW/cm^2 levels, nor did the pulsed field affect performance. The rats exposed to 15 mW/cm^2, however, while showing no significant decrement in performance, did show obvious signs of heat stress.

In the context of behavioral effects, it should be noted that behavior is not a simple process and that behavioral effects represent the summation of different effects in different systems. Such effects could be a response to subtle temperature input signals which may arise in many body structures.

Effect on learning ability. Conditional response studies have indicated alteration in learning as a consequence of microwave exposure (31, 42, 43). Retrograde amnesia and depressed learning have been described in rats exposed to microwaves (44, 45). The field intensity in these studies evidently was quite high.

Alternating arousal and drowsiness effects have been noted in dogs subjected to pulsed UHF fields (31). It has been suggested that the phenomenon of pulsed energy sleep may be related to the effects described above (46). In this technique a low intensity current (0.2 mA) is applied to the brain between occipital and orbital electrodes. This current is pulsed at a rate between 1 and 100 pps, with a pulse duration of 0.3 ms. Under these conditions a sleep-like state (which is apparently quite similar to normal physiological sleep) is observed in the subjects. Pulsed energy sleep has been used as therapy for psychopathologic conditions.

Reported observations in man

Effects in man referrable to CNS sensitivity have been described (14, 42, 47, 48, 49). Most of the reported effects are subjective, consisting of fatigability, headache, sleepiness, irritability, loss of appetite, and memory difficulties. Psychic changes that include unstable mood, hypochondriasis, and anxiety have been observed. Compared to those in control groups, persons working in microwave fields of various intensities complain often of a heavy feeling in their heads, headaches, fatigue, drowsiness in the daytime, irritability, poor memory, and a pain in the heart, usually of the aching, stabbing type. Objective symptoms are bright red, diffuse, persistent dermographia, hyperhidrosis, unstable arterial pressure, and angiopathy of the retina. Autonomic vascular instability is reflected in changes in the electrocardiogram (bradycardia, disturbance in intraventricular conduction). Mental disorders such as anxiety, insecurity, hypochondria, suicidal thoughts, and at a later state, delirium, terror, visual and auditory hallucinations, combined with impairment of sleep have been reported (50). Most of the subjective symptoms are reversible, and pathological damage to neural structure is insignificant. [illegible] the reports are based on subjective rather than objective findings. It should be [illegible] suffering from a variety of chronic diseases may exhibit the [illegible] cardiovascular systems as those reported to be a result [illegible]

Soviet and other East European investigators have contributed most of the reports on human effects of microwave energies; the greatest emphasis is on effects produced at less than "thermogenic" power flux densities (<10 mW/cm²). According to these authors, the responses of an organism to microwave exposure are directly or indirectly referrable to the central nervous system (14, 48, 51).

Neurasthenia syndromes. The reported neurasthenic effects from electromagnetic radiation have been organized into categories by wavelength, organ system, or clinical syndrome. Many of the reports in man can be classified into categories such as: a) neurasthenic syndrome, b) autonomic vagotonic dystonia, and c) diencephalic syndrome (52). All three classes of symptoms have been reported in individuals subjected to microwave fields of "a few mW/cm²" (53). The basic symptomatology and neuropathology underlying all of these syndromes is reportedly due to the functional disturbance created in the central nervous system caused by reported "non-thermal" mechanisms. These effects do not appear in relation to observed rise in body temperature, and are reported to occur at levels far below those required to produce a temperature rise. The symptoms are manifested by weakness, fatigue, vague feelings of discomfort, headache, drowsiness, palpitations, faintness, memory loss, and confusion. Such syndromes are completely reversible in most cases, with little or no time lost from work (20). In contrast, other authors emphasize the resultant time lost from work, and the necessary hospitalization (51).

In regard to the question of neurasthenic responses, Cohen and White (54) have presented an extensive review of neurocirculatory asthenia as a clinical syndrome that has implications in assessing the reported effects of "low level" microwaves. Neurocirculatory asthenia presents as a familial disorder with a mean age of onset of 26 years (range 25-35 years). Twice as many cases are presented in females compared with males. The authors relate that onset of the syndrome in predisposed individuals is usually precipitated or made worse by emotion-provoking circumstances, medical illness, unaccustomed or hard muscular labor (particularly if involuntary), pregnancy, and in various situations in military service. Exact etiological relationships are unknown, but point toward environmental influences and familial predisposition.

Cortical activity. The results of long term neurologic observation of 500 persons exposed to electromagnetic fields were evaluated by Klimkova-Deutschova (55). Most frequent subjective symptoms were: headache, fatigue and sleep disturbances. Less frequent were cases of anxiety, hyperexcitability and vegetative disorders. The objective symptomatology was characterized by labyrinthine deviations and disturbances of pyramidal and extrapyramidal motor systems. The incidence of neurosis was significantly higher than in controls. Experimental physiologic and EEG methods showed mostly reduced vigilance and pathologic records independent of the intensity of the field. The disturbances in metabolic, EEG, and clinical symptoms suggest an impairment of the regulative mechanism in the mesodiencephalic region.

Proposed mechanisms of microwave effects on neural tissues

Some reviewers have suggested that investigations purported to show neurological effects at "non-thermal" microwave intensities do not clearly indicate whether the changes produced by microwaves are due to generalized thermal effects or to more specific influences on particularly vulnerable tissues. The reports of non-thermal effects of microwaves are based on a definition of thermal as being those effects associated with a measurable local or whole organism temperature rise from an equilibrated baseline. Some investigators, however, use the term "thermal" in a somewhat different sense, taking into account the fact that an organism can be affected thermally without demonstrable core temperature rise.

As already pointed out, among the authors that have investigated conditional responses in different animals, there is disagreement in the evaluation of the observed phenomena and understanding of their mechanisms; these studies are complex and require a special investigative approach (34). Measurement of behavior by operant conditioning techniques has only recently been applied to the study of microwave radiation effects. While the study of reflex conditioning is acceptable, it must be emphasized that a reflex response (knee jerk, salivation, etc.) is a lower order, mostly spinal cord performance linked through conditioning to the presence or absence of some stimulus signal (light, bell, etc.), the whole of which forms a simple paradigm (41). In contrast, behavior elicited through operant techniques is of a higher order, more cerebral performance, variants of which can be built into much more complex tasks requiring a high degree of information integration and stimulus discrimination. In short, operant conditioning taps a different level of behavior, for while reflex conditioning fixes a natural response to a novel stimulus, operant conditioning links a novel response pattern to a complex stimulus contingency (56).

In respect to the relationship of body temperature and physiological functions, it is important to realize that temperature input signals arise in many body structures among which the following have been identified experimentally: a) preoptic-anterior-hypothalamus, b) posterior hypothalamus, c) mid-brain, medulla, motor cortex and thalamus, d) spinal cord, e) skin, f) respiratory tract, and g) viscera. All of these except the motor cortex and thalamus have been shown to evoke behavioral and/or physiological responses to changes in local temperature (57). Stress is known to cause the secretion of a corticotropin releasing factor (CRF) which stimulates the pituitary to release adrenocorticotropic hormone (ACTH) which in turn causes the adrenal gland to release corticosterone, a hormone carried back to the pituitary to shut off the release of further ACTH. Both active and passive types of avoidance behavior are potentiated by ACTH and reduced by corticosterone.

Changes may be produced by means of stimulation or variation of the excitability of the peripheral and central parts of the nervous system. Since biological objects are electrically heterogeneous and microwave-range electromagnetic fields (EMF) have a known selective thermal effect on various tissues and organs, a difference between a microwave effect and a neutral heat effect is not necessarily due to an unknown extrathermal factor, but might well be a function of an uneven distribution of heat in the organism which could exert its own peculiar effect.

An electromagnetic field can be reinforced in the region of peripheral nervous tissue causing a temperature rise, even while nearby muscle and skin show no measurable temperature effect (58, 59). When peripheral nerves are heated above a minimum level, they may trigger spontaneously. Thermal stimulation of the peripheral nervous system can produce the neurophysiological and behavioral changes that have been reported. The interaction between the peripheral nervous system and the central nervous system could also account for reported cardiovascular effects (58, 59).

Presman (19, 48) suggests that resonant absorption at superhigh frequencies (gigahertz range) could cause transitions of molecules, especially protein molecules, to excited states. He also discusses changes in the Na^+ to K^+ gradient across cell membranes, owing to different effects of microwaves on degrees of hydration of these ions, as well as changes in cell permeability by the disruption of protein hydration in the cell membrane. It must be emphasized that all this is speculative, with no experimental data given in support (14). The changes in functions of the nervous system produced by microwaves are not specific.

Such changes are produced by any means of stimulation or variation of the excitability of the peripheral and central parts of the nervous system. Hence it can be assumed that the action of microwaves on the CNS may be due to stimulation or variation of the excitability of nervous tissues. The elucidation of the physical and chemical mechanisms of microwaves on excitable structures involves considerable difficulties, since the physical-chemical mechanisms of excitability of living tissue in general is still far from clear (19).

MacGregor (60, 61), who reviewed the literature on the influence of microwaves on the nervous system, has suggested possible mechanisms of "low-intensity" microwave influence on neural function:

A. Direct effect (primary effect on apparatus for neuroelectric ionic fluxes).

1. Direct influence on ionic currents leading in turn to influence on transmembrane potentials in nerve cells.
2. Localized heating
   a. change membrane properties, thereby disrupt transport processes;
   b. induce convection currents, thereby disrupt transport processes;
   c. affect processes of synaptic transmission;
   d. affect processes of excitable membrane.
3. Chemical or structural change in components of membrane, or in apparatus of synaptic mechanisms or of excitable membrane.

B. Indirect effects.

1. Primary effect on cell metabolism
   a. alter by heating or by structural change, properties of membrane, thereby disrupting nutritional transfer;
   b. cause structural change in an enzyme or any critical molecule at any stage of metabolic cycle;
   c. alter by localized heating, processes of metabolism at any critical stage.
2. Primary effect reflects "stress"
   a. neural response to disruption of neuroendocrine control systems;
   b. neural response to disruption of any physiological process;
   c. neural sensory response to field directly or to localized temperature disturbances.

C. Disruption by any physical mechanism of hypophysial, glial or electromagnetic organic control systems. Intracranial electrical fields associated with low intensity microwave irradiation may induce transmembrane potentials of tenths of millivolts (or more), therefore, such externally applied fields may disturb normal nervous function through this mechanism (61).

The resting membrane potential of animal muscle and nerve cells is generally in the range of -70 to -110 mV; animal cells cultured in vitro may show values as low as -10 to -30 mV. Due to their selective permeability, electrical double layers are formed at biological membranes which cause differences of potential across the membranes. Therefore, the membranes are placed within electrical fields that are conditioned by electrical double layers. The amplitude of these fields is considerable. It amounts to 10^5 V/cm with a potential difference of 100 mV and a thickness of membrane of 100 Å. Very high fields would be required therefore to cause a direct effect on nervous tissue.

Microwave fields are only capable of applying a potential to a biological membrane which is many orders of magnitude smaller than the resting potential and, for this reason, should be unable to excite or change normal patterns (62, 63, 64). Using a theoretical approach, based on biophysical principles and electromagnetic field theory, wave propagation and absorption in tissues, Schwan (64, 65) calculated that nervous cell membranes cannot be excited at field strengths below thermal levels at frequencies greater than 100 MHz. Membranes are short-circuited by currents of frequency above 100 MHz. The electrical field strength which exists in a nerve membrane is about 500 kV/cm. The field strengths applied by a microwave field to the human body are infinitely smaller, and hence, cannot evoke stimulation (63).

There is a great deal known about the excitation of membranes by low frequency and DC currents. In these cases, excitation is possible with current densities of the order of 1 mA/cm^2 in tissue. At higher frequencies and particularly at microwave frequencies, much higher current densities are required to cause excitation if it is at all possible. Although it is difficult to perceive, based on the above analysis, how microwave fields can affect excitable biological membranes at power densities less than those which would cause thermal effects (63), it should be appreciated that this is only one way in which excitation of nerve tissue can be elicited. Other direct and indirect interaction mechanisms may be possible.

Bawin et al (66) have reported that electromagnetic fields of 147 MHz, amplitude modulated at brain wave frequencies, influence spontaneous and conditioned EEG patterns in the cat at an intensity of 1 mW/cm^2, which, according to the authors, does not induce an increase in temperature. It should be pointed out, however, that these amplitude modulated 147 MHz fields induced changes in the central nervous system only when the amplitude modulation frequency approached that of physiologic bioelectric function rhythms. No effects were seen at modulation frequencies below 8 Hz and above 16 Hz. Bawin et al (67) have also shown calcium efflux from the chick brain exposed in vitro to 147 MHz electromagnetic fields, amplitude modulated at 9, 11, 16, and 20 Hz. This suggests to the authors that electromagnetic fields may induce conformational changes of the neuronal membrane resulting in displacement of the surface bound cations.

It is apparent that the reports which claim the existence of nonthermal effects are equivocal. Additional research, especially of a more quantitative nature, is needed to clarify this point. "Specific" effects quoted in the literature are biologically interesting but have not been clearly shown to be related to symptoms in man (68). Regardless of what the mechanisms are, the important point is whether or not the effects attributed to these mechanisms do indeed exist, and if they exist, to what extent do they represent harm to the individual.

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MICROWAVE INDUCED ACOUSTIC EFFECTS IN MAMMALIAN AUDITORY SYSTEMS

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SUMMARY

Pulsed microwave fields with incident energy densities of 20 to 40 μJ per cm² per pulse will produce responses in the auditory system of man and animals similar to that produced by auditory stimuli. Recent studies indicate that the responses may be originated from high frequency vibrations induced in the head of the exposed subject by a transient thermal expansion of tissue due to the rapid absorption of the pulsed microwave energy.

A. INTRODUCTION

Perhaps the most widely observed and accepted biological effect of low average power electromagnetic (EM) energy is the auditory sensation evoked in man exposed to pulsed microwaves. The effect which has been observed and studied by Frey [1-3], and Frey and Messenger [4], for more than a decade appears as an audible clicking or buzzing sensation originating from within and near the back of the head corresponding in frequency to the recurrence rate of the microwave pulses. The effect is of great interest since it can be evoked by average incident power levels far below those believed to be of thermal significance. The mechanism of the effect, however, has remained obscure until very recently. Sommer and Von Gierke [5] originally suggested that radiation pressure may be sufficiently high to couple acoustic energy to the inner ear by bone conduction. Frey [6] discounted this hypothesis, however, and did not believe that the interaction was due to transduction of EM to acoustic energy. His belief was based on his failure to observe cochlear microphonic potentials associated with the pulsed microwave stimulation of the auditory systems of cats and guinea pigs and on the low levels of incident power at the threshold for perception by the human subject. Frey and Messenger [4] observed that the loudness of the sensation was proportional to the peak power, whereas, Guy, et al., [7] observed that the threshold of the sensation was proportional to energy per pulse. Frey [8] noted that individuals with loss of auditory sensitivity above 5 kHz could not hear the pulses and Guy, et al., [7] found that sensitivity was significantly reduced if there was decreased auditory sensitivity for frequencies above 4 kHz.

The origin and a clear understanding of the microwave hearing phenomena is important since the present ANSI C95.1 safety standard [9] does not restrict the peak power density as long as the power density, as averaged over any six minute period, does not exceed 1 mW-hr/cm², or 3.6 joules/cm². This is five orders of magnitude greater than the threshold level for producing an audible sensation by a single short pulse.

The important questions that needed answers were: (1) what is the threshold of the effect in man and animals as a function of pulse power or energy, pulse shape, and carrier frequency, (2) what is the locus of action of the effect, i.e., is it initiated at a central or at a peripheral site, (3) is the stimulation due to direct action of the EM fields on the nervous system, or to transduced acoustic energy acting on the auditory system, (4) what is the mechanism of interaction, and (5) why must the high frequency portion of the auditory system be normal for the sensation to be elicited.

Recent studies accomplished the following: (1) the establishment of incident field and modulation characteristics at the threshold for auditory sensation in humans, (2) comparison of activity evoked in four successive levels of the auditory nervous system in the cat due to incident acoustic and microwave pulses, (3) assessment of the deactivation of the cochlea, the known first stage of transduction for acoustic stimuli on the potentials evoked by both forms of pulsed energy, (4) the establishment and quantitation of the transduction of microwave pulse energy to acoustic energy in microwave absorbing materials by optical interferometry, and (5) demonstration that the microwave auditory phenomenon is consistent with and can be explained by the direct conversion of EM energy to acoustic energy in the tissues from the rapid thermal expansion of the tissues. These results, discussed in detail in the following sections, are based on past studies reported by Guy, et al. [10] and Chou, et al. [11].

B. DETERMINATION OF THRESHOLDS OF MICROWAVE EVOKED RESPONSES IN HUMANS

The author and his colleague served as subjects to determine the incident power levels and pulse widths needed to evoke the auditory sensation. A 2450 MHz aperture horn source fed by a 10 kW maximum peak power generator with pulses 1 to 32 μsec wide was used to illuminate the test subject. The subject sat with the back of his head directly in front of the horn 15 to 30 cm from the aperture. Placement of the subject's head in the near zone field of the horn was necessary for evoking an auditory response. The "effective" average power density at the location of the exposed surface of the subject's head was first measured with a Narda 8100 power monitor at high pulse rates and low peak power levels as a function of incident power to the horn without the presence of the subject. The values for higher powers and lower pulse rates were obtained by linear extrapolation from the monitored incident power to the horn in order to prevent damage

to the meter probe. A switch was controlled by the subject to signal the operator of the remote transmitter when an auditory sensation could be heard. Prior to the tests, standard audiograms were taken of the subjects, as shown in Fig. 1. The hearing threshold of the first subject was normal while a pronounced notch at 3500 Hz was noted for both ears of the second subject. Similar results were obtained for both air and bone conduction. The background noise of the exposure chamber was measured at 45 dB re 0.0002 dyne/cm^2 with a sound level meter. The pulses were presented as a train of three pulses 100 ms apart every second to maintain an average power density well below 1 mW/cm^2. The output of the generator was set at the threshold where the pulses could be heard by the subject, as indicated by a light activated by the subject. Table I illustrates the measured incident peak and average power density and the energy density per pulse for subject (1) without ear plugs. It was found that regardless of the peak power and pulse width, the threshold was related to an energy density of 40 μJ/cm^2 per pulse or a peak energy absorption density of 16 mJ/kg, as calculated from a spherical model discussed in this Lecture Series "Biophysics - Energy Absorption and Distribution," Section D. The results for subject (2) were similar except the threshold energy level was approximately 135 μJ/cm^2, or 5 dB higher. When subject (1) used ear plugs, the threshold level reduced to 28 μJ/cm^2. Each individual pulse could be heard as a distinct and separate click and short pulse trains could be heard as chirps with the tone corresponding to the pulse recurrence rate. When the pulse generator was keyed manually, transmitted digital codes could be accurately interpreted by the subject. The threshold for two pulses within several hundred microseconds apart was the same as one pulse with the same total energy as the pulse combination. Though the hearing sensation threshold seemed to be in variance with the peak power and loudness relationship observed by Frey [4], the results were consistent when pulse widths are taken into account, as discussed in Section D.

C. DETERMINATION OF CHARACTERISTICS AND THRESHOLDS OF EVOKED AUDITORY SYSTEM RESPONSES IN THE CAT BY ACOUSTIC AND MICROWAVE PULSES

A series of cats, weighing 2.0 to 3.4 kg, were surgically prepared for recording potentials from various levels in the auditory nervous system while they were exposed to short pulses of both acoustic and microwave energy. Separate groups of cats were used for recording from the medical geniculate nucleus and the round window of the cochlea to compare differences and determine the threshold of evoked potentials to acoustic and microwave stimuli. Recordings were made from the VPL of one animal in order to assess the cross-system CNS responses to applied tactile, acoustic and microwave stimuli. Finally, the effect of cochlear disablement on the interaction of the microwave stimuli with the auditory nervous system was assessed. The results of the experiments are described as follows.

1. The Medial Geniculate Nucleus

Fig. 2 illustrates typical evoked responses recorded from the medial geniculate due to acoustic and 2450 MHz microwave pulse stimulation. The response recordings were made on the x - y recorder based on 40 averages taken with a computer of average transients.

The threshold of the 2450 MHz microwave pulse evoked response as a function of pulse width is shown in Table II. The thresholds for the evoked responses with microwave pulses 0.5 to 10 μsec in duration appear to be related to the incident energy density per pulse at a level about one-half of that which produced audible sensations for the human exposure. The required threshold energy per pulse seems to increase with pulse width for 10 to 32 μsec duration pulses with the exception of the 25 μsec case. The peak absorbed energy density per pulse in the head of the cat was measured by thermographic methods described in this lecture series "Engineering Considerations and Measurements" Section B-6.

Fig. 3 illustrates the thermograms taken of the internal absorbed energy density distribution per 20 μJ/cm^2 of incident energy density for the sacrificed cat head exposed to 2450 MHz and 918 MHz radiation. The peak absorbed energy densities corresponding to the thresholds of evoked responses are also tabulated in Table II and III, based on the thermographic data. The incident energy density per pulse corresponding to the threshold for evoked responses recorded from the medical geniculate body due to 918 MHz radiation, as shown in Table III, differs very little from that for 2450 MHz. Fig. 4 illustrates the relative thresholds averaged over three to five cats for both acoustic and microwave stimuli as a function of background noise. The thresholds for the microwave stimuli varied between 6-33 μJ/cm^2 over the group of cats. As the noise level was increased, there was negligible increase in threshold for the microwave stimuli, moderate increase in threshold for the piezoelectric bone conduction source, and a large increase in threshold for the loudspeaker stimuli. An evoked response from the medial geniculate body of the cat was also obtained for two animals using X band pulses at frequencies between 8.67 GHz and 9.16 GHz. Table IV shows that the required energy per pulse to elicit the responses was significantly higher than required for the other frequencies. For this case, the X band horn had to be placed within a few centimeters from the exposed brain surface of the animal (through the 1.0 cm diameter electrode access hole in the skull). No response could be elicited for an animal in which the electrode access port through the skull was limited to the diameter slightly larger than the probe. When the skull was bared, there still was no elicited response. After the hole in the skull was enlarged, however, a response was obtained.

2. Round Window of the Cochlea

In another series of the animals, activity from the round window of the cochlea was recorded in response to acoustic clicks and 2450 MHz microwave pulses. The acoustic clicks were supplied by two methods: (1) air conduction by loudspeakers; and (2) bone conduction by a piezoelectric crystal cemented to the skull. Acoustic stimuli and microwave pulses elicited activity at the round window, as shown in Fig. 5. The first trace of the figure illustrates the composite

cochlea microphonic and N_1 and N_2 auditory nerve response elicited by a loudspeaker pulse from the first animal. The cochlea microphonic was quite strong in amplitude reproducing the decaying oscillatory response shape of the loudspeaker (measured by optical interferometry, as discussed in Section D). When the auditory system of the same animal was stimulated by microwave pulses, a microwave artifact and a clear N_1 and N_2 auditory nerve response was seen, but there was no evidence of a cochlea microphonic as indicated on the second trace in Fig. 5. Frey [6] had discounted the role of the cochlea in microwave acoustic effects, partly on the basis of not observing a microphonic in either cats or guinea pigs. We have found, however, in some animals, that the cochlea microphonic is considerably reduced (third trace in Fig. 5) or not present at all (fourth trace in Fig. 5) when the auditory system of the animal is stimulated by an acoustic pulse. Furthermore, Wever [12] has pointed out a number of factors that would prevent the observance of a cochlear potential, especially when the stimulus intensity is low. He cites work, for example, in which auditory thresholds in cats, as determined by behavioral levels, were established as being 40 dB below the stimulus level, first effective level in producing cochlear mircrophonic potentials of sufficient magnitude to be identified with the convential oscilloscope display. Thus, considering the fact that the microwave pulse generator is capable of only providing a 10 to 17 dB increase in pulse energy over that corresponding to the threshold of evoked responses, the absence of a microwave evoked cochlea microphonic in the cat did not rule out theories based on EM to acoustic energy transduction. This was later resolved by use of a more sensitive preparation with better energy coupling, as described in Section E. The capability of the evoked auditory effect in producing potentials at CNS sites other than auditory is illustrated in Fig. 6. The first trace illustrates the normal response recorded at the medial geniculate as a result of acoustic stimuli. The second trace illustrates the cross-modal acoustically evoked response as recorded from the VPL, whereas, the third trace represents the normal response in the VPL due to an electric shock applied to the tactile receptors at the right forepaw of the animal. The last three traces show that the microwave stimuli will also produce the same cross-modal responses. Thus, it is clear that evoked potentials due to microwave stimuli could be recorded at CNS sites other than those corresponding to the auditory nervous system. This leaves open the possibility that evoked potentials recorded from any location in the CNS could be misinterpreted as indicating a direct microwave interaction with the particular system where the recording is made.

3. Effect of Cochlear Disablement on the Interaction of Microwaves with the Auditory System.

Nine cats were surgically prepared for recording potentials in three brain sites evoked by acoustic and microwave stimuli. Loci in which potentials were observed were the eighth cranial nerve, the medial geniculate nucleus, and the primary auditory cortex. The effect of cochlear disablement on these potentials was evaluated.

The subjects, weighing from 2.0 to 3.4 kg, were assigned to three groups of three. The surgical preparation and details of the experiment have been reported previously by Taylor and Ashleman, [13]. When it was established for each case that responses were obtained with both acoustic and microwave stimuli, the cochlea was disabled by careful perforation of the round window with a micro-dissecting knife and aspiration of perilymph. Both cochlea were destroyed in the experiments involving the medial geniculate nucleus and auditory cortex, sites assumed to have some bilateral representation. Cochlear destruction resulted in total loss of all evoked potentials, even with full available peak power used for both the acoustic and microwave stimuli and with increasing number of signals averaged on the computer of average transients. The data strongly supported the contention that the microwave auditory effect was exerted on the animal in the same manner as that of conventional acoustic stimuli. The results lead one to examine more closely Frey's [3] contention that the auditory effect cannot be a result of transduction of EM to acoustic energy. The following section describes a study aimed toward gaining some insight pertaining to this mode of interaction.

D. QUANTITATION OF EM TO ACOUSTIC ENERGY TRANSDUCTION IN LOSSY DIELECTRIC MATERIALS

Frey's [3] argument that the auditory effect cannot be a result of EM field forces on biological materials was based in part on an analysis by Sommers and Von Gierke [5]. The latter authors directly compared radiation pressure to the pressure required for free sound field bone conduction threshold at 1000 cycles. Frey's threshold values for microwave induced auditory effects appeared far too low to be consistent with the radiation pressure theory. Also, the comparison was incorrectly made between microwave pulses and a 1000 Hz acoustic tone rather than acoustic pulses. Finally, since the microwave energy is capable of penetrating deep into the tissue, volume forces, stresses, and pressures can be set up in many ways due to the sharp field gradients in the complex dielectric medium.

The threshold for audibility of narrow 20 to 500 usec airborne acoustic pulses at recurrence frequencies much less than 100 pulses per second has been determined by Flanagan [14] to be proportional to the energy per pulse or to the product of the pulse duration and the square of the pressure. Based on Flanagan's data, corrected for transducer characteristics, the threshold pressure corresponds to 1.26×10^{-2} dyne/cm^2 for a 20 μsec pulse. There is some uncertainty as to what the bone conduction threshold would be for pulses. According to Zwislocki [15], the difference between air and bone conduction thresholds for continuous wave sound varies from 40 dB at 10 KHz to 60 dB at 1 KHz. Since the pulse frequency spectrum certainly spans this frequency range, we would expect the range of the bone conduction threshold to fall between 1.26 and 12.6 dyne/cm^2 for a free field 20 μsec pulse. Based on the acoustic transmission coefficient of 2 from air to soft tissue, the pressure in the tissue would be in the range of 2.5 to 25

dyne/cm^2. The maximum radiation pressure that a 20 μsec 40 μJ/cm^2 microwave pulse would exert on a highly conducting surface would be 1.33×10^{-3} dyne/cm^2, which is too low to explain the effect by a surface pressure. A surface pressure relationship is also incompatible with Flanagan's [10] results and our observations concerning the dependence on the hearing threshold on pulse energy. The acoustic pulse energy is proportional to the product of pulse width and square of the pressure while the EM pulse energy is directly proportional to the product of the induced pressure and pulse width. Frey and Messenger [4], on the other hand, found for pulse widths greater than 50 μsec that loudness of microwave evoked auditory sensation was proportional to the peak power of the applied pulse when the pulse energy was kept constant by decreasing the width, T, as the peak power was increased. Their data show, however, for the narrow 1-30 μsec pulse width range we are concerned with, the loudness did not vary.

Although the above observations did not support the radiation surface pressure hypothesis, they did not rule out other EM to acoustic energy transduction processes. At the frequencies where the auditory effect is most pronounced, the EM energy which penetrates and is absorbed deep in the tissues of the head can produce volumetric forces by various modes of interaction. Two types of pressures, much greater than radiation pressure, can be produced in tissues exposed to microwave pulses. These include electrostrictive and thermal expansion forces proportional to the square of the electric field in the material. Although the elctrostrictive forces are unknown for biological materials exposed to microwave frequencies, a rough estimate of the possible magnitudes may be obtained from the equation given by Stratton [16] for electrostatic field applied to a non-compressible dielectric fluid.

$$p = \frac{1}{6}\,\varepsilon_o E^2(\kappa + 2)(\kappa - 1) \tag{1}$$

where E is the electric field, p is the pressure increase over that at a location where $E = 0$, ε_o is the permittivity of free space, and κ is the dielectric constant of the liquid.

Although the thermal expansion forces are also unknown for biological material, a theoretical and experimental analysis of the conversion of bisible electromagnetic radiation from a Q-switched ruby laser to acoustic energy by thermal expansion due to absorbed energy in various liquids was made by Gournay [17]. It was shown that the pressures vastly exceeded radiation pressure. Foster and Finch [18] extended Gournay's analysis to the case of physiological Ringer's solution exposed to microwave pulses and showed theoretically and experimentally that pressure changes far in excess of radiation pressures could produce significant acoustic energy in the exposed medium. It is very significant to note that the audible sounds could be produced by rapid thermal expansion associated with only a 5×10^{-6}°C temperature rise in the medium due to the absorbed EM energy. The maximum pressure, p, induced in a semi-infinite absorbing liquid medium due to an incident microwave EM pulse normal to the surface was derived by Gournay [17] as

$$p = \frac{3C\beta I_o}{2JS}\,(1 - e^{-\alpha CT}) \quad \ddagger \tag{2}$$

for a free surface and

$$p = \frac{3C\beta I_o}{JS}\,(1 - e^{-\alpha CT/2}) \tag{3}$$

for a constrained surface, where C is the elastic wave velocity, β is the linear coefficient of thermal expansion, S is the specific heat, α is the absorption coefficient for the medium, J is the mechanical equivalent of heat, I_o is the EM power intensity at the surface, and T is the pulse width. Gournay's analysis also showed that the maximum conversion efficiency (energy of propagated elastic wave divided by energy of transmitted EM wave) for the energy transduction was

$$N = \frac{C\beta^2 I_o}{2\rho S^2 J^2}\,F(\alpha CT) \tag{4}$$

where

$$F(\alpha CT) = (1-e^{-\alpha CT}-\alpha CTe^{-\alpha CT})/\alpha CT \tag{5}$$

for a free surface and

$$F(\alpha CT) = (\alpha CTe^{-\alpha CT} + 3e^{-\alpha CT} + 2\alpha CT-3)/\alpha CT \tag{6}$$

for a constrained surface where ρ = the density of the medium. The maximum value of $F(\alpha CT)$ is 0.3 for $\alpha CT = 2.0$ for the free surface and 2.0 at $\alpha CT > 10$ for the constrained surface.

Though the above analysis is based on an exposed semi-infinite medium with an absorption coefficient of α, we would expect acoustic pressures within the same order of magnitude to be induced in more complex media exposed to microwave pulses. If we assume a peak absorbed power

‡ Equations include corrections for errors that appear in the original reference.

density in the brain of 0.4 W/kg per 1 mW/cm^2 incident power density based on a theoretical analysis discussed in this Lecture Series "Biophysics - Energy Absorption and Distribution," Section D, and also assume that the Equations (2) or (3) may be applied to this case, the calculated acoustic pressure in the brain of approximately 2.2 - 3.0 $dyne/cm^2$ due to an incident 20 μsec, 40 $\mu J/cm^2$ EM pulse would be above the computed internal threshold pressures. The estimated electrostrictive force of 1.4×10^{-2} $dyne/cm^2$ from Equation (1) would be far below the threshold of hearing range and much lower in amplitude than that due to the rapid thermal expansion conversion process.

It is of interest to note that for the constrained surface where $\alpha CT < 5$ (corresponding to pulse widths less than 30 μsec for Ringer's solution exposed to 2450 MHz microwaves) that $F(\alpha CT)$ is approximately equal to $\alpha CT/2$, implies that the propagated elastic wave energy is proportional to the square of the incident electromagnetic wave energy. This is consistent with our experimental observations that the hearing threshold is constant with pulse energy for pulses less than 32 μsec and with Frey's observations that loudness increased with peak power for pulse widths greater than 50 μsec.

In solid, more compressible materials such as bone, electrostrictive and thermal expansion forces could be much larger. The fact that the interaction of microwave pulses with non-liquid lossy dielectric materials can produce sufficient volumetric forces and displacement in the material to be audible to nearby observers has recently been observed by Sharp, et al [19]. Audible sounds were elicited from microwave anechoic absorbing material by peak pulse energies corresponding to those producing the auditory sensation to exposed humans.

We found in our laboratory that the air-conducted sounds could be elicited from microwave absorbing materials of either porous or solid composition. No audible air-conducted sounds could be obtained from lossy liquids or gells exposed to the microwave pulses nor from good conductors (silver painted plastic disks) or dielectrics (plastics with low dielectric constant). Weak audible sounds could be heard from exposed samples of low loss but high dielectric constant material. The prerequisite for audibility seems to be an electrical conductivity and/or dielectric constant within the range of human tissues such that the absorbed or stored EM energy is distributed over a large volume of the illuminated material. With only surface absorption such as with silver-coated samples, there was no detectable interaction. This is consistent with Frey's observations, and ours, that the lowest thresholds of interaction occur at frequencies where absorption in the head occurs over a large volume.

In order to study the interaction with solid materials more quantitatively, a Michelson interferometer was assembled, as show in Fig. 7. A Helium—Neon laser beam was split so that one beam reflected from a small mirror attached to a dielectric test sample would form an interference pattern with a second beam reflected from a fixed mirror illuminating a pinhole in a plate. A fiber optics guide was connected to an oscilloscope, waveform averager, and an x-y plotter. The sample dielectric was illuminated with pulsed microwaves using the same 918 MHz power source and power measuring equipment used for the human and animal experiments. The sample interferometer and exposure apparatus was electrically isolated from the photomultiplier and associated electronics by a shielded room.

Shifts in the fringes of the interference pattern due to vertically polarized microwave field induced displacements of the test object and mirror were sensed by the photomultiplier through the fiber optics pathway, passing through the wall of the shielded room. The system was calibrated to measure displacement as a function of the brightness of a fringe line over the pinhole by noting the full dynamic range of the oscilloscope voltage excursion (proportional to brightness) when the mirror was displaced one-half light wavelength or more. The sensitivity of the system was enhanced by repetitive averaging of the triggered responses of the sample. The samples of dielectric tested for acoustic transduction properties were 5 cm diameter solid cylinders from 0.5 to 4.0 cm long. Four different types of materials were tested; three consisted of laminac 4110 polyester plastic loaded with varying amounts of acetylene black to produce electrical condictivities close to human tissue, as shown in Table V, and the fourth consisted of a sample of Eccosorb ANW-77 microwave absorber. The electrical properties of the disk were measured by standard transmission line techniques. The interferometer was also used to determine the displacement waveform of the piezoelectric crystal and the loudspeaker used in the animal experiments.

In order to relate the internal fields in the samples to the acoustic responses of the sample, the internal energy density absorption and electric field patterns were measured in the disks by the thermographic technique discussed in this Lecture Series "Engineering Considerations and Measurements" Section B-6.

Fig. 8 illustrates displacement recordings made with the interferometer. The first waveform is that of the piezoelectric crystal excited with a 20 μsec 40 V pulse, the second is that of the loudspeaker excited with a 20 μsec 0.16 V pulse, the third the typical response of a lossy dielectric disk exposed to a microwave pulse, and the last is the response of a 5 cm diameter 3 cm long cylinder cut from a slab of spongy Eccosorb ANW-77 absorber. The latter was interesting since the displacement per unit of incident energy was greater than for any of the other dielectric materials tested, probably due to its lower density and greater compressibility. The slight delay between the application of the pulse and first sign of displacement is also of interest. The displacement waveforms provided both maximum displacement and frequency of oscillation information useful for

making estimates of internal pressures. In all cases, the acoustic response of the disks to the incident microwave pulses were audible to nearby observers.

Table VI summarizes the measured power absorption and acoustic characteristics of the exposed disk samples. The measured dielectric properties and sample thicknesses are given in the first three columns. The respective measured peak absorbed energy densities per pulse, the maximum rms electric field strengths, and the maximum measured displacements of the flat surface of the disks are tabulated in the next three columns. A rough estimate of the internal peak pressure vibration, p, in the disk was determined for each case from

$$p = \frac{2\pi\delta\rho v}{T_0} \tag{7}$$

where δ is the measured displacement, $\rho = 1.12 \times 10^3$ kg/m^3 is the measured density, $v = 2400$ m/sec is the measured velocity of sound propagation, and T_0 was the period of vibration of the disks.

In order to appreciate the significance of the calculated pressures, it is useful to compare them to pressures derived from Equation (2) for the semi-infinite medium (free surface) using the same internal measured field strengths and dielectric properties. The mechanical properties of the nonloaded polyester plastic were used. These calculated pressures are tabulated in the last column of Table VI. It is clear that the pressures listed in the last two columns of the table exceed the calculated radiation pressure of 3.6×10^{-2} dyne/cm^2 by many orders of magnitude. It is also clear that the induced oscillatory pressures in the exposed sample disks are far above those predicted for a fluid with the dielectric properties of brain matter. The disk oscillations produce sounds similar to the microwave evoked "clicks" sensed in the human auditory system. The large difference in pressures between that calculated for liquids and the solid disk are certainly consistent with our failing to detect any displacement in liquid or gell materials. Foster and Finch's [18] measurement with a more sensitive hydrophone did detect the acoustic disturbances in the liquids, however. He theorized that the actual hearing sensation is mediated by high recurrence rate multiple reflections of the acoustic disturbances within the head or portions of the skull. This is evidenced by the fact that the band limited 50 Hz — 15 kHz noise did not effect the threshold of evoked potentials in the cat to the microwave stimuli as it did for the acoustic stimuli. It is known that cats perceive higher frequency through both air and bone conduction. The nature of the induced acoustic disturbance is further elucidated in the following section.

E. MICROWAVE INDUCED COCHLEAR MICROPHONICS IN GUINEA PIGS

Previous failures to observe microwave evoked cochlear microphonics (CM) in experimental animals exposed to microwave pulses are probably due to: (1) the frequency of CM is higher than the frequency response of recording equipment, (2) the microwave energy is too low to elicit a detectable CM, and (3) the CM may be buried in a large microwave artifact. Once the above problems are avoided or minimized the existence of microwave evoked cochlear microphonics can easily be demonstrated as done by Chou, et al. [11].

They used guinea pigs weighing 400-600 gm which were anesthetized with pentobarbital sodium (40 mg/kg, IP) and allowed to breathe normally through an inserted tracheal cannula. After exposing either the right or left bulla, a fine (microwave transparent) carbon lead was placed against the round window and cemented onto the bulla. An indifferenct electrode was connected ot the nearby tissue. A test was then made to determine the magnitude of the cochlear produced by acoustic clicks. If the maximum amplitude was greater than 0.5 mV, the head of the guinea pig was placed through a hole into a circular waveguide. The waveguide was matched so the microwave power propagating in the TE_{11} mode was completely absorbed by the 75g head of the subject. By transferring all of the available power of the 10 kW microwave pulse generator directly to the head of the animal, they were able to produce an average absorbed power density of 1.33 joules/kg in the head. This is one order of magnitude greater than the maximum energy per pulse delivered in previous experiments by radiation fields. It is estimated that a radiation energy density of 0.125 to 3.32 mJ/cm^2 per pulse would have to be delivered to produce the same effect. Microwave pulse artifacts were considerably reduced by placing the irradiation equipment and subject in a shielded room and transmitting the recorded signals via coaxial leads to a preamplifier outside the room. The sound level in the region of the head of the guinea pig was about 55 dB mainly due to the noise produced by the microwave pulse generator. The animals were radiated intermittently for 1.5 min by 918 MHz microwave pulses of 1-10 µsec in duration and 100 pps repetition rate at various peak power levels below 10 kW. The responses were recorded on a magnetic tape system with a frequency response of 80 kHz. After a 3-5 hr experiment, the animals were sacrificed, either by an euthanesia agent or anoxia. The animal responses were recorded until the physiological potentials disappeared completely. The recorded data was averaged off-line by a computer of average transients.

Fig. 9 shows the electrical responses at the round window of a guinea pig stimulated with acoustic clicks. The response consists of cochlear microphonics (CM) and both N_1 and N_2 nerve responses. The inversion of the CM due to reversing the polarity of the electrical pulses delivered to the speaker is also seen in Fig. 9.

Fig. 10 shows the round window response of the same guinea pig stimulated by microwave pulses. In addition to N_1 and N_2, the cochlear microphonics immediately follow the microwave stimulus. A time expansion of the CM is also shown in the figure. The microwave evoked CM, approximately 50 kHz

in frequency, 50 μV in amplitude, and 200 μsec in duration were observed in five preparations, satisfying the acoustic sensitivity tests.

A comparison of the CM evoked by microwave pulses of 10 μsec, 5 μsec, and 1 μsec at the same peak power of 10 kW is shown in Fig. 11. These traces are averages of 400 responses replayed from the tape. Each of the traces shows an artifact at the left of the figure. Due to the limited frequency response of the tape recorder, the transient due to the microwave artifact is 60 μsec instead of 30 μsec, as seen for the on-line record in Fig. 10. Although the presence of CM is evident, the onset of these CM is masked by the artifact. Fig. 11 shows that the frequency of the CM stayed the same but as indicated at the right of the figure, the amplitude of the CM dropped for narrower pulses since there was less energy absorption. This figure also indicates that the oscillations of CM occurred at approximately the same latency after the onset of the microwave pulses. We conclude from Fig. 11 that a physiological response time-locked to the onset of microwave pulses is generated within the guinea pig's cochlea. Since the CM is followed by auditory nerve activity (N_1) after an interval of time that closely resembles that seen in the acoustically stimulated ear (Fig. 9), it seems reasonable to assign this event to hair cell activation.

After the animal was sacrificed, either by anoxia or an euthanesia agent, the N_1 and N_2 responses diminished earlier than the CM. (The same phenomenon occurs during acoustical stimulation). After the animal's death, neither CM nor N_1 and N_2 could be observed, although the artifact persisted. This result indicates that the 50 kHz oscillatory signal is a genuine physiological response.

As shown in Fig. 12, the amplitudes of CM and N_1, as well as the latency of the N_1 response, varied as a function of the average energy absorption density per pulse. The CM amplitude saturation seen with high intensity microwave stimulation finally resembles its behavior at high sound pressure levels [20].

The 50 kHz CM frequency seems related to a resonance phenomenon dependent on the size of the animal skull as suggested by Foster and Finch [18]. Since individuals with high frequency hearing losses (above 10 kHz) cannot hear the microwave pulses, the frequency of microwave CM probably lies between 10-20 kHz for the human. For a head size like that of the cat, the frequency of the microwave CM can be estimated to be between 20-50 kHz. This estimate is also consistent with the fact that a masking noise of 50 Hz - 15 kHz did not affect the threshold of evoked response in the medial geniculate of cats.

F. TEST OF MICROWAVE INDUCED HEARING IN RATS

Recently we have been able to demonstrate that rats can hear pulsed microwaves. In this study, a food deprived rat was restrained in a plexiglass cylinder and trained on continuous reinforcement to make a nose-poke operant thereby breaking a photo cell beam and receiving a food pellet for the response. Subsequently, the rat was trained to make the same response on an ascending series of variable ratio (VR) reinforcement schedules until the animal was responding on a VR10 at over 20 responses/min. Finally, the rat operant was brought under stimulus control by differentially reinforcing and extinguishing the response during the presence or absence, respectively, of a 7kHz speaker click of approximately 60 dB intensity at a 100 Hz repetition rate. When the animal was consistently responding at 80%, or better, correct (in the "go" interval), it was considered at criterion. Subsequently, the animal was probed with pulsed microwaves, during various "no go" intervals (periods of non-responding) and the effect of this procedure was to induce responding in the rat, thus demonstrating that price behavioral control by auditory clicks was generalized to microwave clicks.

G. CONCLUSIONS

It has been shown that the threshold for microwave pulse evoked auditory sensations or responses in both humans and cats is related to the incident energy per pulse with values of approximately 20 $\mu J/cm^2$ for cats to 40 $\mu J/cm^2$ for humans for pulses less than 30 μsec wide. This corresponds to an estimated peak absorbed power density of 10 to 16 mJ/kg as measured in the cat head and approximately 16 mJ/kg as estimated for a human head. This energy density is capable of increasing the tissue temperature by only 5×10^{-6}°C. As background noise (50 Hz - 15 kHz bandwidth) was increased, the threshold for evoked responses in the medial geniculate nucleus of the cat remained stable for pulsed microwave stimuli but increased for acoustic stimuli. This would tend to indicate that the microwaves may be interacting more with the high frequency portion of the auditory system. With the exception of the absence of the cochlea microphonics at the round window, all evoked potentials in cats due to microwave stimulation were similar to those due to stimulation by acoustic clicks from loudspeaker (air conduction) and a piezoelectric transducer (bone conduction) attached to the skull. It was shown, however, that the cochlea microphonics could be recorded in guinea pigs exposed to microwave pulses when sufficient incident power was used. The frequency of the microphonics (50 kHz) in guinea pigs supports a hypothesis that a vibration is set up in the head corresponding to its accustical resonant frequency. Since cochlear destruction resulted in total loss of all evoked potentials due to microwave and acoustic stimuli, there is strong support for the contention that the microwave auditory effect is exerted on the animal in the same manner as conventional acoustic stimuli. Radiation pressure was ruled out as a probably cause of the evoked response since it is both too low in magnitude and inconsistent with the known threshold behavior for acoustic pulses. The most likely mechanism of electromagnetic field interaction appears to be

conversion of EM energy to acoustic energy due to thermal expansion in the tissues within the head. This is based on their relatively high predicted and measured values in liquid and solid materials exposed to microwave pulses. This hypothesis is further reinforced by the fact that the behavior of the measured threshold characteristics with pulse width agree with those predicted by the thermal expansion theory. It has been shown by means of a Michelson interferometer that displacements and forces induced in lossy dielectric disk samples by incident microwave pulses are many orders of magnitude above the threshold values for hearing. The interaction with the absorbing material was sufficiently strong that it was audible to nearby observers.

A prerequisite for interaction with the material is that the dielectric constant or conductivity be sufficiently high and the frequency proper to allow for a penetration of energy and loss over an appreciable fraction of the volume when the object is exposed to a microwave pulse. Microwave absorber materials used to reduce reflections and solid materials with the dielectric properties close to human tissues seem to fulfill the above requirements. The fact that the sounds are mediated by pulse energy levels sufficient to raise the tissue temperature only 5×10^{-6}°C points out the extreme care that one must exercise in classifying an effect as thermal or non-thermal based simply on the level of temperature increase.

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TABLE I THRESHOLD OF MICROWAVE EVOKED AUDITORY RESPONSES IN

HUMAN (2450 MHz 3 PULSES/SEC) BACKGROUND NOISE 45 DB

PEAK INCIDENT POWER (W/cm^2)	AVG INCIDENT POWER (μW/cm^2)	PULSE WIDTH (μs)	ENERGY DENSITY/ PULSE (μJ/cm^2)	PEAK ABSORBED ENERGY DENSITY PER PULSE[4] (mJ/kg)
40	120	1	40	16
20	120	2	40	16
13.3	120	3	40	16
[illegible]	120	4	40	16
8	120	5	40	16
4	120	10	40	16
2.33	105	15	35[2]	14
2.15	129	20	43	17
1.8	135	25	45[3]	18
1.25	120	32	40	16

1. Thresholds for subject #1 in Fig. 1
2. 28 with earplugs.
3. 135 for subject #2 in Fig. 1
4. Based on absorption in equivalent spherical model of head.

TABLE II THRESHOLD EVOKED AUDITORY RESPONSES IN CAT

2450 MHz (ONE PULSE/SEC) BACKGROUND NOISE 64 DB

PEAK INCIDENT POWER DENSITY (W/cm^2)	AVG INCIDENT POWER DENSITY (μW/cm^2)	PULSE WIDTH (μs)	INCIDENT ENERGY DENSITY PER PULSE (μJ/cm^2)	PEAK ABSORBED ENERGY DENSITY PER PULSE (mJ/kg)
35.6	17.8	0.5	17.8	10.1
17.8	17.8	1	17.8	10.1
10.0	20.3	2	20.3	11.6
5.0	20.3	4	20.3	11.6
4.0	20.3	5	20.3	11.6
2.2	21.6	10	21.6	12.3
1.9	28.0	15	28.0	15.9
1.7	33.0	20	33.0	18.8
0.6	15.2	25	15.2	8.7
1.5	47.0	32	47.0	26.7

Research was conducted according to the principles enunciated in the "Guide for Laboratory Animal Facilities and Care" prepared by the National Academy of Sciences National Research Council.

TABLE III THRESHOLD OF EVOKED AUDITORY RESPONSES IN CAT

918 MHz (ONE PULSE/SEC) BACKGROUND NOISE 64 DB

PEAK INCIDENT POWER DENSITY (W/cm^2)	AVG INCIDENT POWER DENSITY ($\mu W/cm^2$)	PULSE WIDTH (μs)	INCIDENT ENERGY DENSITY PER PULSE ($\mu J/cm^2$)	PEAK ABSORBED ENERGY DENSITY PER PULSE (mJ/kg)
5.80	17.4	3	17.4	12.3
3.88	19.4	5	19.4	13.8
2.26	22.6	10	22.6	16.0
1.37	20.6	15	20.6	14.6
1.17	20.6	20	20.6	16.6
0.97	24.3	25	24.3	17.2
0.80	28.3	32	28.3	20.0

TABLE IV THRESHOLD OF EVOKED AUDITORY RESPONSES IN CAT*

X BAND (ONE PULSE/SECOND)

BACKGROUND NOISE 64 DB

	APPROXIMATE VALUES
PEAK INCIDENT POWER (W/cm^2)	14.8 TO 38.8
AVG INCIDENT POWER ($\mu W/cm^2$)	472 TO 1240
PULSE WIDTH (μs)	32
ENERGY DENSITY/PULSE ($\mu J/cm^2$)	472 TO 1240

*Application of power directly to top of exposed skull required to elicit responses.

TABLE V COMPOSITION AND ELECTRIC PROPERTIES OF DIELECTRIC DISKS

FREQUENCY (MHz)	MATERIAL+		DIELECTRIC CONSTANT ϵ'	CONDUCTIVITY σ (mho/m)
	ACETYLENE BLACK CONTENT* (%)	LAMINAC 4110** (%)		
918	1	99	6.41	0.266
918	2.5	97.5	14.12	1.817
918	5	95	20.00	3.316
2450	1	99	5.25	0.370
2450	2.5	97.5	10.47	2.126
2450	5	95	16.45	3.734

+A small amount of catalyst was added.

*Product of Shawinigan Products Corp.

**Product of American Cyanamid Co.

TABLE VI COUPLED EM ENERGY[1] AND ACOUSTIC PROPERTIES

OF EXPOSED DIELECTRIC DISKS

DIELECTRIC PROP. ϵ'	σ(mho/m)	SAMPLE THICKNESS (cm)	MAX ABSORBED ENERGY DENSITY PER PULSE (J/kg)	PEAK ELECTRICAL FIELD (KV/m)	MEASURED DISPLACEMENT (Å)	CALCULATED PRESSURE[2] FOR DISK (DYNE/cm^2)	PRESSURE FOR SEMI-INFINITE DIELE. MEDIUM[3] (DYNE/cm^2)
6.41	0.266	4	0.96	14.19	28	993	2397
		2	1.02	14.66	36	2553	2559
		0.5	2.24	21.73	47	4546	5619
14.12	1.817	4	1.33	6.40	36	1277	1263
		2	1.72	7.29	38	2696	1638
		0.5	7.00	14.69	48	4643	6651
20.00	3.316	4	1.32	5.06	48	1703	1053
		2	1.66	5.32	66	4682	1164
		0.5	4.84	9.04	74	7157	3360

1. 918 MHz, 20 μ second, 1.07 mJ/cm^2 incident microwave pulses.

2. Based on Equation (7).

3. Magnitude of estimated field induced pressure in semi-infinite dielectric medium based on Equation (2).

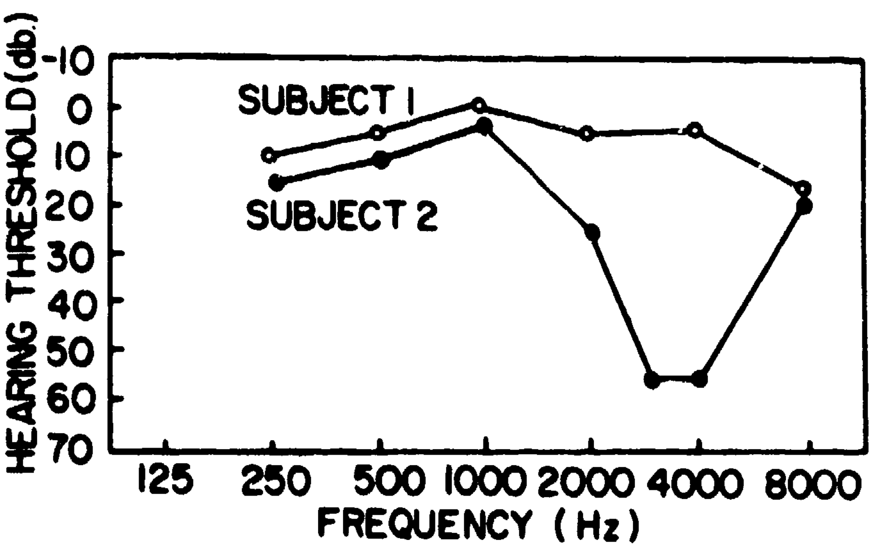

Fig. 1 Audiograms of human subjects used for determining thresholds of audibility to pulsed microwaves.

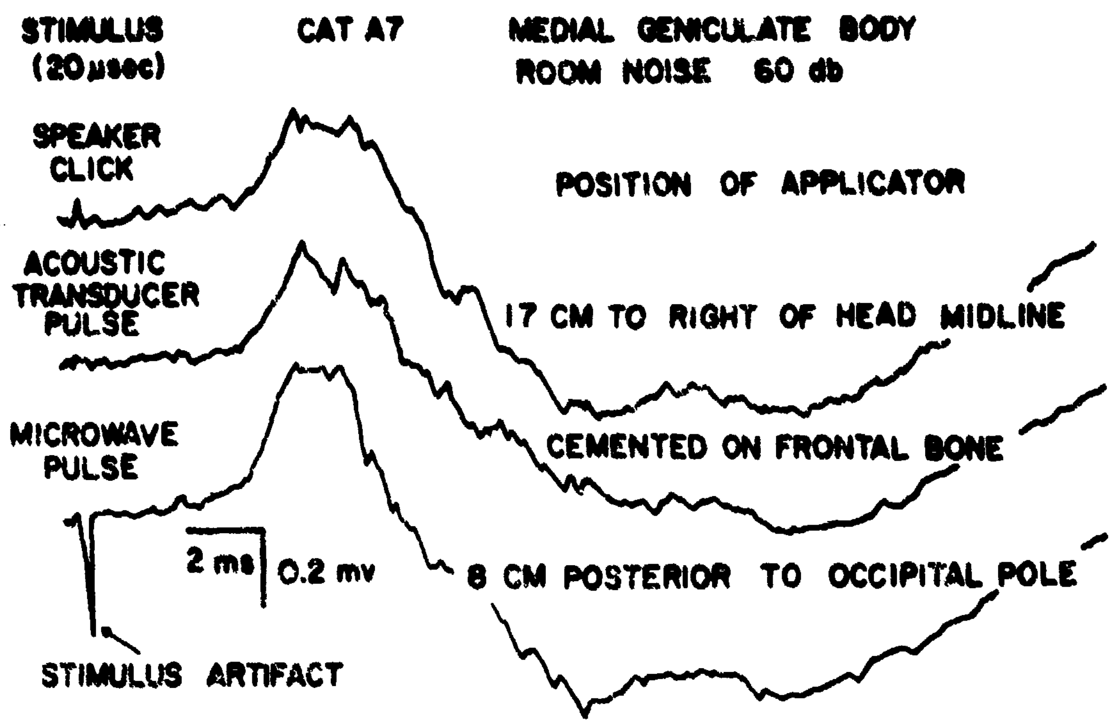

Fig. 2 Evoked responses recorded from medial geniculate body of the cat.

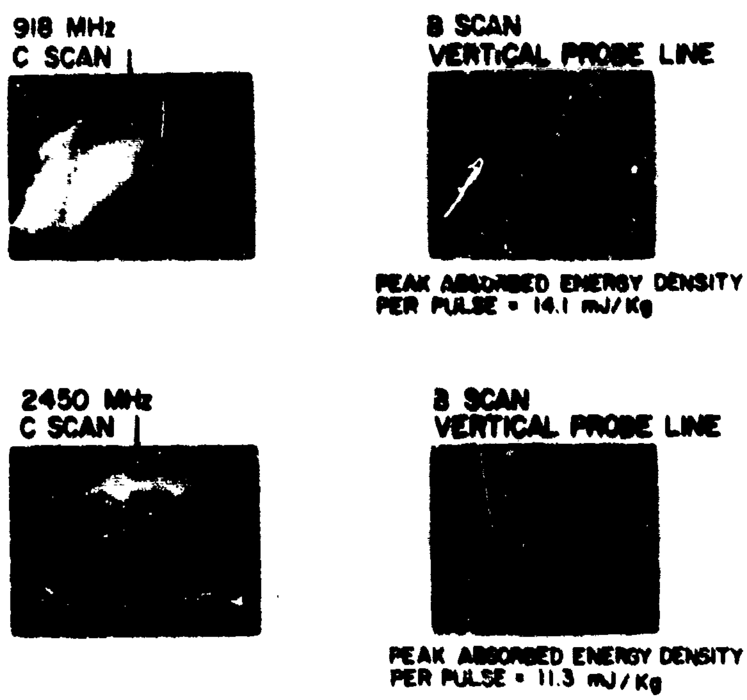

Fig. 3 Thermograms showing absorbed energy density patterns (per pulse) in the head of cats exposed to 918 MHz and 2450 MHz 20 uJ/cm^2, 20 μsec incident pulses.

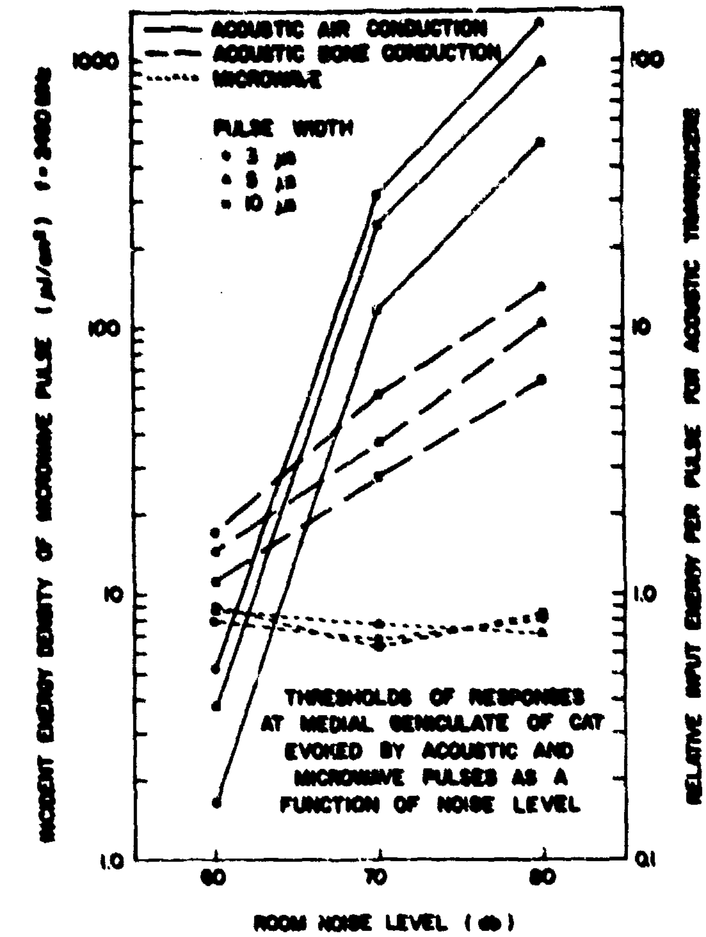

Fig. 4 Threshold of evoked medial geniculate responses (averaged for 3 to 5 cats) as a function of background noise.

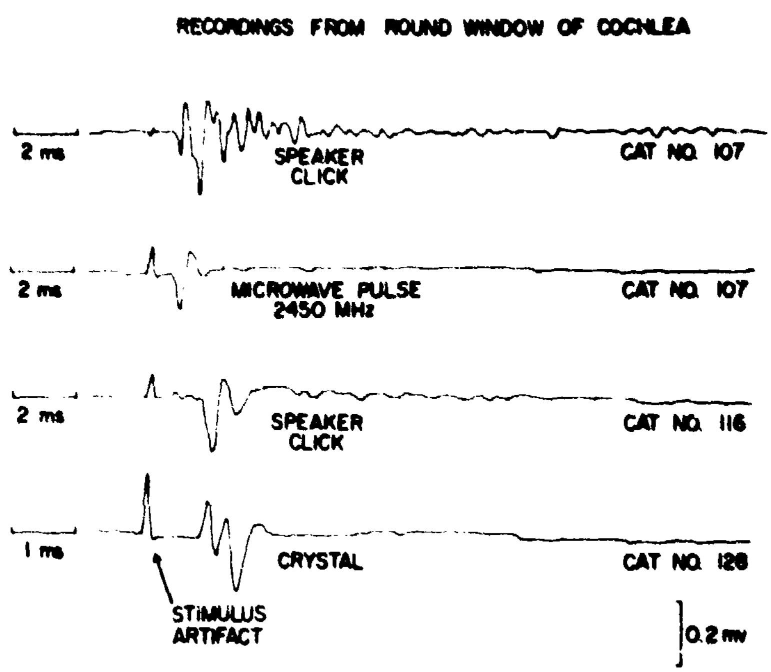

Fig. 5 Responses in the round window of the cat cochlea due to acoustic and microwave stimuli.

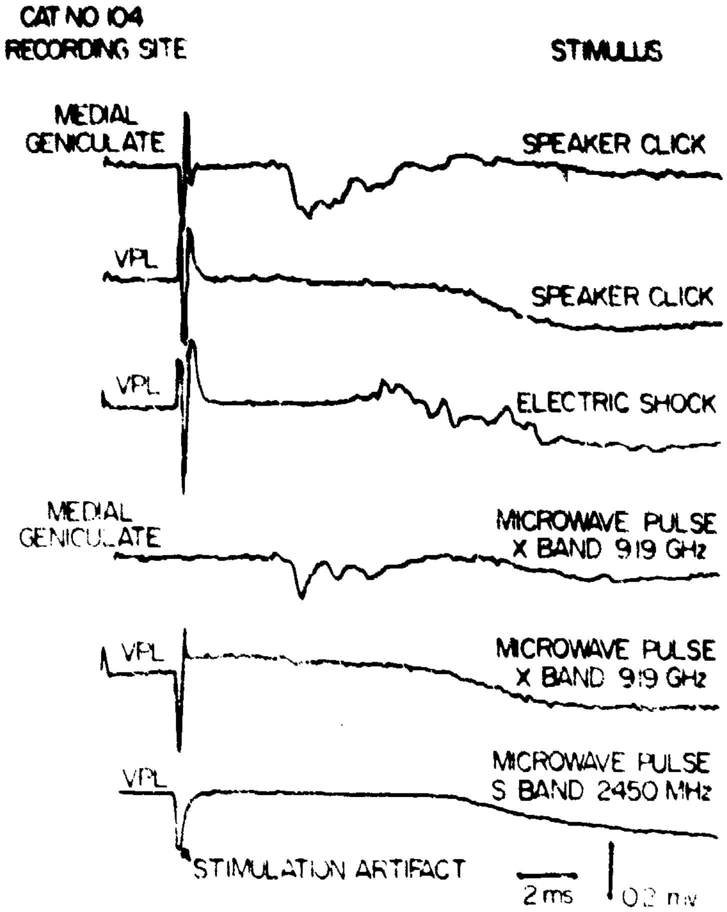

Fig. 6 Cross-modal CNS responses to acoustic and microwave stimuli.

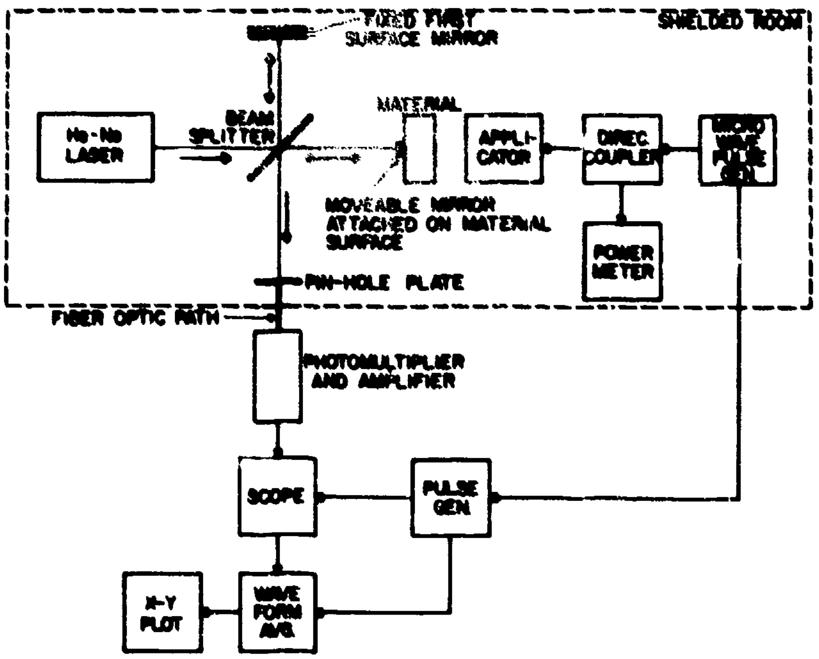

Fig. 7 Michelson interferometer for measuring displacements in dielectric material illuminated by microwave pulses.

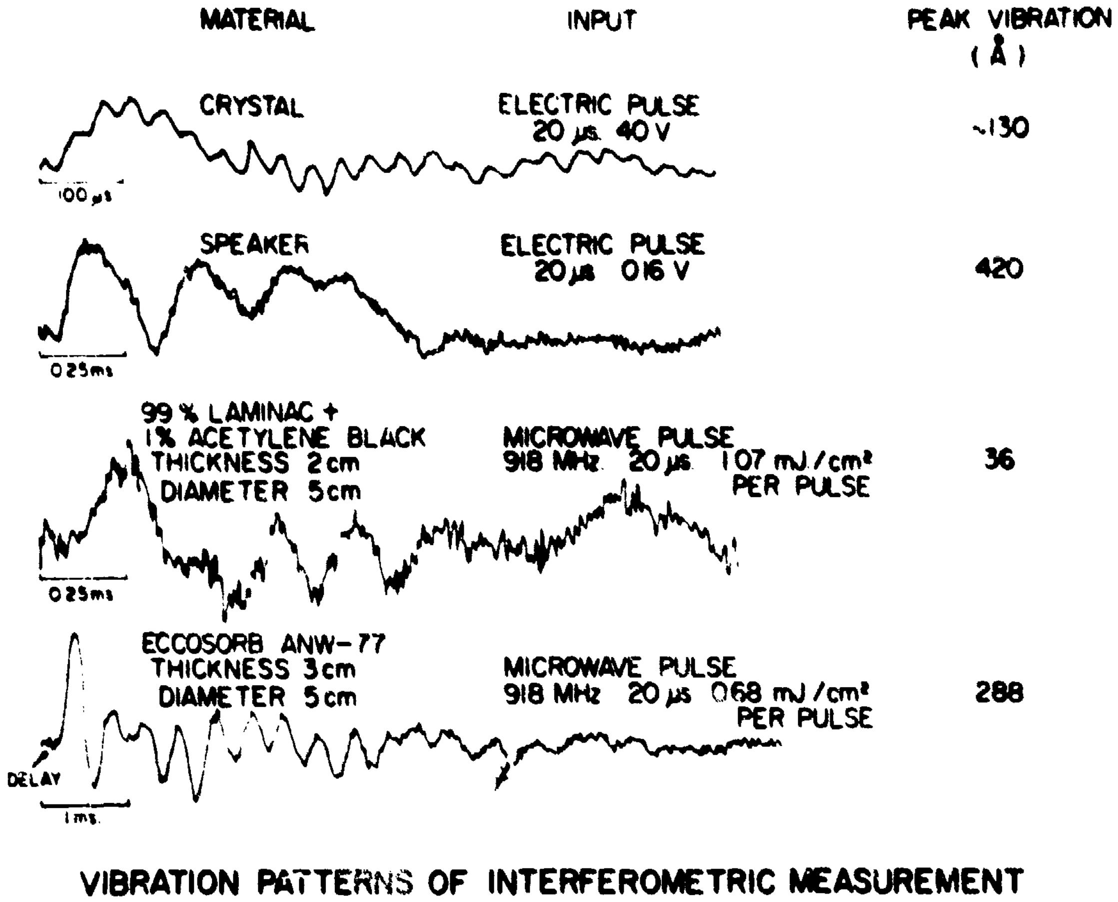

Fig. 8 Displacement waveforms for pulsed acoustic transducers and for lossy dielectrics illuminated with microwave pulses.

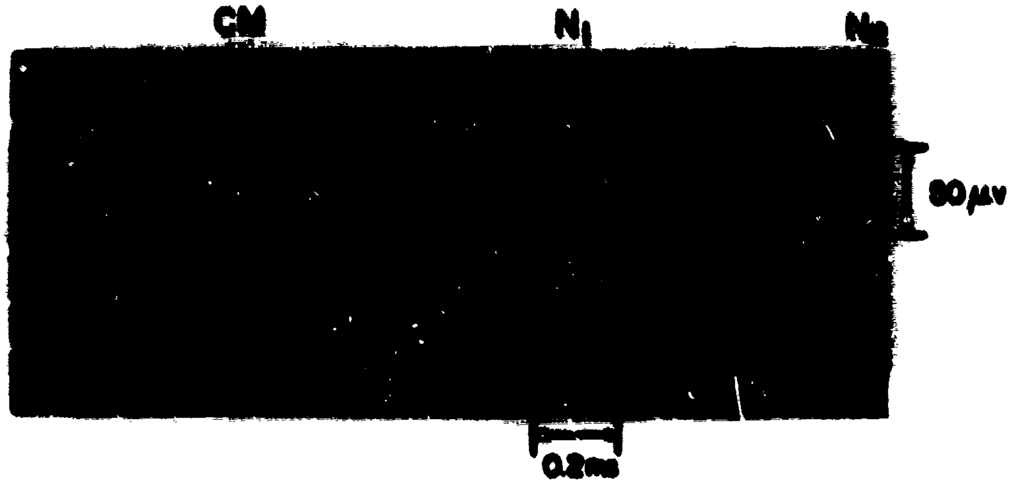

Fig. 9 Round window responses evoked by single acoustic clicks; click phase is reversed in upper and lower traces.

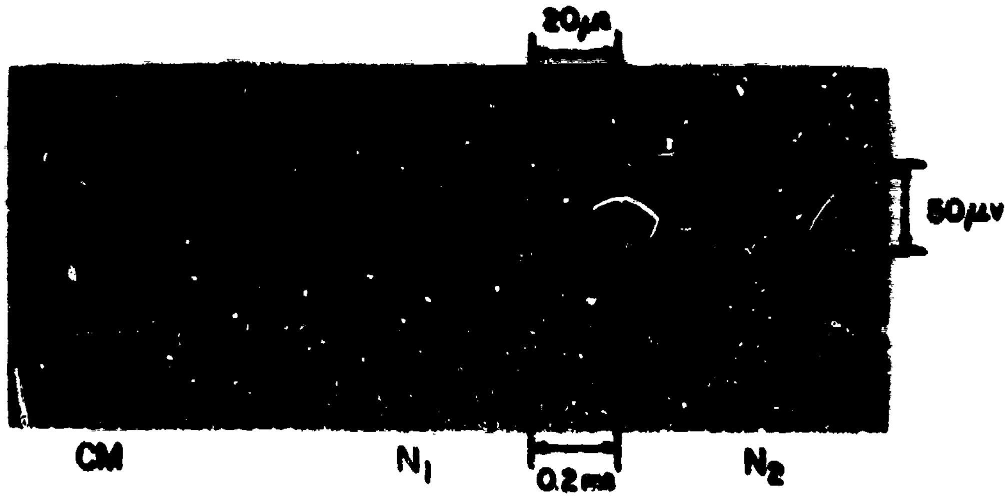

Fig. 10 Round window responses evoked by a single 918 MHz microwave pulse, (10 usec pulse width, 1.33 joule/kg average absorbed power density per pulse). Upper trace is expansion of the initial 200 usec of lower trace.

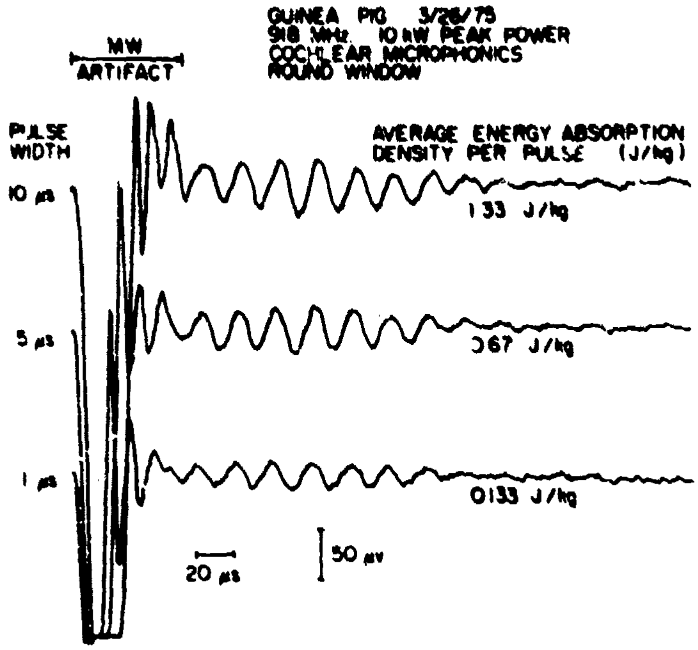

Fig. 11 Average of 400 CM responses evoked by 918 MHz microwave pulses, 10, 5, and 1 µsec pulse width at the same peak power, 10 kW. The average energy absorption density per pulse is shown below and to the right of each trace.

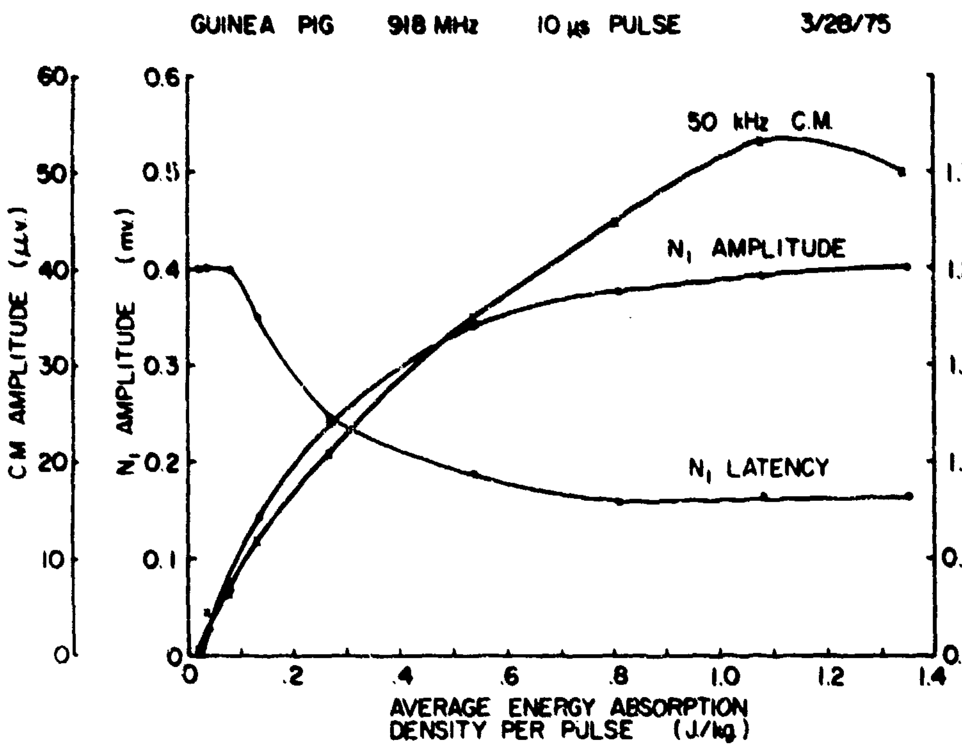

Fig. 12 Amplitudes of microwave induced CM and N_1, and latency of N_1 as a function of the average energy absorption density per pulse.

BIOLOGICAL EFFECTS OF ULTRASOUND

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1. INTRODUCTION

Ultrasound comprises mechanical vibrations occurring in the frequency range above 20 kHz and extending in practice to above 10 GHz. Its physical and biological properties vary very widely over this frequency range. Correspondingly there is a very wide range of practical applications, each with different possibilities for exposure of human beings to ultrasonic energy.

This lecture will discuss the following three main areas of knowledge that are necessary to understand the possible hazards from the use of ultrasound.

(a) The actual physical exposures encountered by humans in various activities.

(b) The nature of the biophysical interactions of ultrasound with human tissues.

(c) The evidence for and against significant changes being produced in living systems by the action of ultrasound.

A brief discussion of protection procedures will also be given.

2. PHYSICAL EXPOSURES

Humans may be exposed to ultrasound in a variety of situations. In general this will be either deliberate exposure for medical reasons (diagnostic or therapeutic) or inadvertent exposure in industrial or occupational situations. In the medical field there is now considerable interest in measuring the actual levels of exposure of patients and some reasonably good data are available. For occupational exposure however, no systematic data on human exposure levels seems to be available. A summary of exposure levels measured for medical applications is given in Table I and a list of some of the major occupational sources of ultrasonic exposure is given in Table II.

TABLE I. Measured Ultrasonic Exposure Parameters in Common Medical Applications

Parameters	Pulse-Echo Diagnostic	Doppler Diagnostic	Therapy
Nominal Acoustic Frequency (MHz)	1 - (15)	2 - 5	1 - 3
Average Acoustic Power (mW)	0.3 - 21	19 - 24	0-25,000
Peak (Space-Time) Intensity ($W.cm^{-2}$)	1.4 - 95	0.003 - 0.023	0 - (25)
Peak Pressure Amplitude (bar)	2 - 17	0.1 - 0.3	0 - (8.5)
Pulse Duration (μs)	1		

TABLE II. Occupational Sources of Ultrasonic Exposure of Humans

Source	Approx. Frequency Range	Comments
Industrial Cleaners	20 - 80 kHz	Skin contact possible. Order of 1 kW. Some power in audible range.
Machining and Welding	20 kHz	
Flaw detection	1 - 10 MHz	Comparable to Medical pulse-echo.
Sonar	10 - 500 kHz	High peak power (cavitation limited)

3. BIOPHYSICS OF ULTRASOUND INTERACTIONS

At least two physical mechanisms of ultrasonic action can be identified as being biologically effective: cavitation and heat generation. There is a possibility that additional mechanisms may exist, but evidence for this is not clearly established.

The extent to which cavitation can be made to occur in the human body *in vivo*, even under extreme ultrasonic exposure conditions, is still very uncertain. Diagnostic conditions of exposure (low intensities and/or very short pulse durations) are generally insufficient to induce cavitation even in nonviscous liquids and it is thus particularly unlikely to occur *in vivo*. The biological effects of cavitation in liquid cell suspension systems is predominantly that of cell death by disintegration. Associated mechanical damage to surviving cells has been demonstrated but no clear evidence has been found to indicate that this is in its nature either mutational or otherwise indicative of significant hazard.

Heat generation can be an effective mechanism for ultrasonically induced biological change in intact tissue systems, which are characterized by relatively high ultrasonic attenuation coefficients (of the order 0.1 $(MHz)^{-1}$ for soft tissues) and low thermal mobility. Where however low average intensities are involved, for example in diagnostic exposures, temperature rises may amount to no more than a small fraction of a degree.

A phenomenon that can be significant in leading to heat induced damage is that of mode-conversion, which characteristically results in localized deposition of heat in the region of bone surfaces.

Biophysical evidence for other possible mechanisms of action of ultrasound is insufficient for any useful assessment of hazard and further evidence in this direction must at present be sought from the results of empirical, screening type investigations.

4. SPECIFIC EVIDENCE ON HAZARD FROM ULTRASOUND

In addition to the above biophysical considerations, there are two main lines of evidence on the existence of hazard from human exposure to ultrasound: from screening investigations and from epidemiology.

4.1 Screening Investigations

A problem that runs through the whole question of the possible "hazard" associated with the use of ultrasound is that there is no *a priori* indication of the nature of the hazard that might be found to occur. The most serious type of consequence would seem to be that of genetic or teratogenic change and most of the screening work has been in this direction. Some such investigations, primarily concerned with diagnostic-type medical exposures, are referred to in earlier reviews (see bibliography). More recently, systematic investigations have been carried out on mice irradiated under conditions very greatly in excess of those used in diagnosis, with no resulting evidence for effects either on specific genetic damage or on such factors as gestation time, fetal weight, litter size and incidence of resorptions and abnormalities in pregnant mice and their litters. Some investigators have reported contrary findings but in general these are of doubtful validity.

One line of investigation to which considerable effort has been devoted over the past few years has been that of the possible induction of chromosomal aberrations in living cells exposed to ultrasound. This is a technique widely used in other branches of toxicology, particularly ionizing radiation, and its intensive application in ultrasound was stimulated in particular by a report of positive effects following rather low intensity (8mW/cm^2) exposures. A number of useful follow-up studies, including some attempts by the original author to repeat his own work, have failed to confirm the original findings and, although this may continue to be an interesting and important area of investigation, the current concensus of evidence here is overwhelmingly against the existence of any effect, at least under medical exposure conditions.

4.2 Epidemiology

In any discussion of the hazards of medical or occupational exposures, regardless of the nature of the particular agency that may be under suspicion, no completely satisfactory conclusion can be drawn that does not rely on evidence from humans: "the proper study of mankind is man". Epidemiology is a demanding science and to produce fully satisfactory evidence on the safety of ultrasonic exposures would call for a study involving large numbers of subjects, extending over a period of a number of years and preferably designed on a prospective basis. No such study has yet been carried out although one, at least, is now being planned. Meanwhile the only evidence of this nature comes from a retrospective study on 1114 apparently normal pregnant women examined by diagnostic ultrasound in three different centres and at various stages of pregnancy. A 2.7% incidence of fetal abnormalities was found in this group as compared with a figure of 4.8% reported in a separate and unmatched survey of women who had not had ultrasonic diagnosis. Neither the time in gestation at which the first ultrasonic examination was made, nor the number of examinations, seemed to increase the risk of fetal abnormality.

No comparable studies appear to have been made on occupational exposures to ultrasound and, apart from occasional reports of discomfort and possible temporary hearing impairment (now believed to be due to audible sound components sometimes associated with ultrasound), no accounts of serious ill effects or accidents have been published.

5. PROTECTION PROCEDURES

No official recommendations on health protection in the use of ultrasound are in existence.

For ultrasonic therapy there is an unofficial agreement limiting the acoustical output of generators to 3 W cm^{-2} (averaged over a transducer face of area approximately 5 cm^2). However, actual practice does not always conform to this figure. Appropriate recommendations on the calibration of ultrasonic therapeutic devices have been made by the International Electrotechnical Commission in their document IEC 150.

For medical diagnosis there is no corresponding agreement, although users are often concerned to limit the exposure of patients, in a manner consistent with good diagnostic performance, by controlling output power, pulse repetition frequency or total irradiation time.

Until good and representative measurements of the acoustic intensity levels encountered in practice have been carried out it will not be possible to make satisfactory recommendations about control of occupational exposure to ultrasound. Meanwhile the following practical protection measures can be applied :

(a) As far as possible limit power levels employed and the duration of their application.

(b) Avoid unnecessary acoustic contact between machine and operator (in particular use the shielding properties of air and low density materials).

(c) Recognize that the ear (because of its design and function) may be a critical organ particularly where associated audible sound energy may occur.

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ENGINEERING CONSIDERATIONS AND MEASUREMENTS

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SUMMARY

Quantitation of the biological effects in subjects exposed to electromagnetic fields requires that both the fields in the environment and within the exposed tissues be measured. Fields in the environment can be measured by means of standard off-the-shelf field survey meter sensors consisting of small dipoles with diode or thermocouple-type transducers for converting microwaves or RF energy to proportional electrical signals. Fields and associated absorbed power density in the tissues can be measured by means of thermocouples, thermistors, fiber optic liquid crystal sensors, and thermography. The quantitation of fields associated with exposure of test subjects can be significantly simplified by a judicious choice of exposure techniques.

A. INTRODUCTION

In an earlier section of this series, "Biophysics - Energy Absorption and Distribution" patterns of absorbed power density in many different configurations of biological tissues exposed to various EM sources were discussed from a theoretic . standpoint. The determination of absorbed power by theoretic methods, however, are limited only to simple geometic shapes. The only practical way to determine these patterns for irregular shapes and relate them to exposure fields is through carefully designed instrumentation. There are two important classes of instruments; the first pertains to measurement of the exposure conditions or the applied fields, and the second pertains to measurement of fields and associated power absorption within the tissues. The latter presents some very formidable problems indeed.

Electromagnetic fields or quantities related to the fields can be measured both *in situ* and *in vivo* in test animals or even humans by means of implanted microwave diodes, thermocouples, and thermistors. Thermocouples and thermistors were used extensively in the past for measuring the temperature rise in tissues exposed to radiation. There are several problems associated with the use of thermocouples or thermistors to ascertain absorbed power: 1) the element senses only the temperature of the tissue which is also a function of other mechanisms such as thermal diffusion, blood flow, and the thermoregulatory characteristics of the animal; 2) if the sensor is left in the tissue during irradiation, it can be directly heated by the RF fields or it can significantly modify the fields and the associated temperature rises; and 3) the sensor is relatively insensitive to low power densities.

A method that eliminates many of the above problems is the use of thermography. The method has been used to measure surface temperature in exposed hairless animals [1]. It is most useful in the indirect measurement of internal temperature and absorbed power density patterns in animal carcasses or phantom models of human or animal tissues exposed to EM fields [2].

The problem of field measurements both outside and inside of the exposed subject can be greatly simplified through the use of appropriate exposure techniques which are uniquely associated with the type of subject under study. The techniques and typical results obtained through their use are discussed in detail in the following sections.

B. METHODS OF MEASUREMENT

1. Radiation Survey Meters

Since the Radiation Control for Health and Safety Act was passed in 1968 [3], there has been considerable improvement in radiation survey meters for measuring radiation power densities in air. Typical designs are illustrated in Fig. 1. The meter usually consists of a sensor consisting of two or more orthogonal electric dipole elements, each terminated in a thermocouple or microwave diode element and coupled via small-diameter high-resistance wires to a voltmeter calibrated to record power density directly in mW/cm^2.

A thermocouple described by Aslan [4] consists of a pair of thin-film vacuum-evaporated electrothermic elements that function as both antenna and detector. The sensor materials are antimony and bismuth deposited on a plastic or mica substrate, all secured to a rigid dielectric material for support. The length of the dipoles is small compared to a wavelength to allow the unit to monitor power with minimum perturbation on the RF field. The dc output of the sensor is directly proportional to the RF power heating the element. The hot and cold junctions of the electrothermic element, separated by 0.75 mm, are in the same ambient environment, thereby providing an output relatively independent of ambient temperatures. With the thin-film elements oriented at 90° to each other and connected in series, the total dc output is independent of orientation and field polarization about the axis of the probe and is proportional to the square of the electric field vector. If the proportionality constant relating E to H is known or remains constant, such as 377 Ω in the far field, the output can be calibrated in terms of power density. In the near field, the meter will read an effective power density or simply the square of the electric field divided by 377. Lead wires carrying the dc output of the thermocouples are shielded with ferrite materials and

maintained perpendicular to the plane of the antenna. They will, therefore, be invisible to the propagating wave when the antenna is placed parallel to the phase front. The dc output is connected to an electric voltmeter calibrated to read field density directly in mW/cm^2. The meter, shown in Fig. 2, has an appropriate time constant to read average power when the meter is used to measure modulated RF power density. The disadvantage of this meter configuration is that the output from the sensor is extremely frequency-sensitive and the meter must be calibrated for each frequency. In addition, since the dipoles lie in one plane, the meter sensing probe must be oriented so probes are parallel to the EM wave front. Sometimes this is impossible in near-zone fields since there may be field components in three orthogonal directions. Aslan [5] has developed an improved isotropic wide-band field sensor. The sensor is composed of three elements arranged in orthogonal configuration. The elements shown in Fig.3 are lossy and are heated by the field. Each element consists of a series of thin-film thermocouples deposited on a plastic substrate. The instrument is used where the wavelength is long compared to the length of the thermocouple strips and since their resistance is very high, field pertubations are negligible and the heating in each strip is proportional to the square of the electric field component along it. A signal is obtained from each strip that is proportional to the E^2 heating of the element. The signals from 3 to 4 cm long elements are summed to provide a signal proportional to the square of the total electric field. Since the elements are relatively long, however, the instrument can only be used where the field variation is small over the region occupied by the three orthogonal sensing elements. The meter shown in Fig. 4 is designed to operate over the .85 to 13 GHz frequency range for measuring electric field strengths of 9 to 610 V/m or .02 to 100 mW/cm^2.

Another type of broadband isotropic field sensor has been described by Bowman [6]. This sensor consists of three orthogonal dipoles with diode detectors connected between the arms of the dipoles. The signals from the dipoles are conducted independently through high-resistance leads that are transparent to the microwave fields to the instrumentation, as shown in Fig. 5. For low intensity fields that have wavelengths that are large compared to the dipole lengths, the detected signals from each orthogonal element of the field sensor are proportional to the square of the corresponding electric field components. The signals are equalized and fed to a summing amplifier which has an output proportional to the $|E|^2$. For fields with high intensities, the non-linear characteristics of the summing amplifier provide an extended dynamic range. The instrument is calibrated to display $(1/4)\ \epsilon_0 |E|^2$, the electric field density. The meter, shown in Fig. 6, is useful in the frequency range .03 to 3 GHz for electric field strengths of .9 to 4750 V/m, or 0.0002 to 6000 mW/cm^2.

Survey meters of the type described above can be used meaningfully only to measure power density in a radiation-type field or the square of the electric field intensity in a near-zone field. This information is not enough, however, to indicate what is happening in the tissues of the exposed subject. These problems are discussed in detail in the following sections.

2. Glass Probe and Thermocouple Combination

All the problems associated with measuring temperature and absorbed power density in tissues with thermocouples discussed previously can be eliminated through a technique that utilizes a small diameter plastic or glass tube sealed at one end and implanted at the location where a measurement of the absorbed power is desired. The tube, illustrated in Fig. 7, is long enough so that the open end, fitted with a plastic guide, protrudes from the tissue. A very small diameter thermocouple is inserted into the tube with the sensor located at the probe tip and an initial temperature is recorded. The thermocouple is quickly withdrawn from the tube and the animal is exposed under the normal conditions of the experimental protocol with the following exceptions. Instead of using the power level normally chosen for a given experiment, a very high power burst of radiation of duration sufficient to produce a rapid but safe temperature rise in the tissue is applied to the animal. The thermocouple is then rapidly returned to its original position and the new temperature is recorded for several minutes. The temperature versus time curve is then extrapolated back in time to the period when the power was applied and, based on the density and specific heat of the tissue, the absorbed power density is calculated from the difference between initial and final extrapolated temperatures. The short exposure period insures that there is no loss of heat due to cooling or diffusion, so integration of the energy equation over the short time period t gives $W_a = 4.186 \times 10^3$ $c\Delta T/t$, where c is the specific heat of the tissue, ΔT the temperature change in degrees Celsius, and t the time of exposure in seconds. The measured absorbed power can then be used to relate the input power of the source to the absorbed power in the tissue under normal lower power exposure conditions.

3. Thermistor with High Resistance Leads

Miniaturized thermistors with sufficiently small diameter high resistance leads can be used for certain measurements in tissues exposed to EM fields. They must be used with caution, however, with a clear understanding of their limitations. Even though the high resistance leads do not appreciably modify the general field patterns in the tissues, small currents can be induced in the wire leads producing very high current densities at the termination of the leads at the thermistor. These field concentrations can produce effects in the cells immediately surrounding the thermocouple tip and produce sufficient heating to modify the temperature seen by the thermistor itself. These problems can be alleviated somewhat by surrounding the thermistor with a dielectric material to prevent the fringing fields from concentrating in the tissues themselves. This would tend to increase the response time of the thermistor, however, due to the thermal barrier produced by the dielectric material. The second problem can be eliminated by extending the thermistor leads beyond the sensing element a sufficient distance to remove the element from the fringing fields. This latter approach, however, cannot be indiscriminately used to monitor temperatures in animals where biological effects are simultaneously being monitored since in many cases effects on cells near the terminals may contribute to the general effects.

4. Microwave Diodes

The same techniques involving microwave diodes and dipoles that are used for direct measurement of fields in air can also be used in tissues. There are difficulties, however, since the ratio of the dipole length to feedline separation must be kept large to maintain accuracy while at the same time the dipole must be sufficiently short to implant with a probe. Bowman [7] proposes an implantable diode using three orthogonal dipole and diode combinations of this type with small high resistance plastic filaments as lead wires. Johnson and Guy, [11] have used a microwave diode with pigtail leads cut to 1/2 cm as a dipole antenna to make field measurements at the brain surface of a cat. The major problem with this type of sensor is that it must be calibrated for each tissue that it is placed in to account for changes in dipole source impedance. With a proper design, however, the impedance problem could conceivably be solved. Recent work by Bassen [8] has been directed toward this type of measurement, but at this time there does not seem to be any configuration that has been tested in biological tissues.

5. Fiber Optic Liquid Crystal Probe

Johnson, et al., [9] has developed a probe for measurement of temperature in tissues under exposure to electromagnetic fields. The probe is essentially transparent to the electromagnetic field since it does not possess metallic parts. It utilizes fiber optics to transmit information to and from a sensor tip that consists of a liquid crystal thin film. The sensor tip, which is inserted into the tissue at the point where temperature or dosimetry information is needed, consists of a bulk liquid crystal encapsulated between two nested mylar® cups and fitted over the tip of the fiber optic bundle. One-half of the fiber optic strands is used to transmit red light from a light-emitting diode into the liquid crystal material, and the other half carries scattered red light back to a photo detector. Any temperature change in the liquid crystal shifts the color center resulting in a change in backscattering of the red light. The device is capable of providing an output voltage change of 20-40 mW/°C. Tests have shown that the probe is capable of measuring the true temperature in tissues exposed to electromagnetic fields without producing any changes in the field configuration in the tissues.

6. Measurement by Thermography

Guy [10], and Johnson and Guy, [11] have described a method for rapid evaluation of absorbed power density in tissues of arbitrary shape and characteristics when they are exposed to various sources, including plane wave, aperture, slot, and dipoles. The method, valid for both far- and near-zone fields, involves the use of a thermograph camera for recording temperature distributions produced by energy absorption in phantom models of the tissue structures. The absorbed power or magnitude of the electric field may then be obtained anywhere on the model as a function of the square root of the magnitude of the calculated heating pattern. The phantoms are composed of materials with dielectric and geometric properties identical to the tissue structures they represent. Phantom materials have been developed which simulate human fat, muscle, brain and bones. These materials have complex dielectric properties that closely resemble the properties of human tissues reported by Schwan [12]. The modeling material for fat may also be used for bone and the synthetic muscle can also be used to simulate other tissues with high water content. A simulated tissue structure composed of these modeling materials will have the same internal field distribution and relative heating pattern in the presence of an electromagnetic source as the actual tissue structure. Phantom models of various tissue geometries can be fabricated as shown in Fig. 8. They include circular cylindrical structures consisting of synthetic fat, muscle and bone, and spheres of synthetic brain to simulate various parts of the anatomy. The models are designed to separate along planes perpendicular to the tissue interfaces so that cross-sectional relative heating patterns can be measured with a thermograph. A thin (0.0025 cm thick) polyethylene film is placed over the precut surface on each half of the model to prevent evaporation of the wet synthetic tissue. In using the model, it is first exposed to the same source that will be used to expose actual tissue. The power used on the model will be considerably greater, however, in order to heat it in the shortest possible time. After a short exposure, the model is quickly disassembled and the temperature pattern over the surface of separation is observed and recorded by means of a thermograph. The exposure is applied over a 5- to 60-s time interval depending on the source. After a 3- to 5-s delay for separating the two halves of the model, the recording is done within a 5-s time interval, or less. Since the thermal conductivity of the model is low, the difference in measured temperature distribution before and after heating will closely approximate theheating distribution over the flat surface except in regions of high temperature gradient where errors may occur due to appreciable diffusion of heat. The thermograph technique described for use with phantom models can be used on test animals. The animal under test or a different animal of the same species, size and characteristics must be sacrificed, however. The sacrificed animal is frozen with dry ice in the same position used for exposure conditions. It is then cast in a block of polyfoam and bisected in a plane parallel to the applied source of radiation used during the experiment. Each half of the animal is then covered with a plastic film and the bisected body is returned to room temperature. The same procedure used on the phantom model is then used with the reassembled animal to obtain absorbed power patterns over the two-dimensional internal surface of the bisected animal.

C. THERMOGRAPHIC MEASUREMENTS OF THE ABSORBED POWER IN REGULAR SHAPED PHANTOM TISSUE MODELS

1. Plane Tissue Layers Exposed to Rectangular Aperture Sources

Fig. 9 illustrates the thermograms obtained by Guy [10] for a plane bilayered simulated fat and muscle model exposed to waveguide and aperture sources of varying height B, as illustrated in Fig. 14. Since the specific heat and density of the fat is a factor 0.35 to 0.45 smaller than that of the muscle, the temperature curves in the fat ($0 \leq z_1 < 2.0$) must be reduced by this factor to be representative of absorbed power. When this reduction is made there is close correspondence between these experimental results and the theoretical results discussed by the author in a previous section of this series, "Biophysics - Energy Absorption and Distribution." The thermograph camera was set to obtain a "C" scan, displaying a two-dimensional picture of the entire area heated (intensity proportional to temperature) in the x-z plane, as shown in the upper left portion of each collection of thermograms. The scale on the oscilloscope indicator was set so that one large division was equal to 2 cm. The horizontal midline with the small subdivisions on each thermogram corresponds to the z axis of the geometric center of the aperture and perpendicular to the flat interfaces of the phantom tissue. The vertical midline with the small subdivisions corresponds to the fat and muscle interface. Photographs of the "B" scans shown on the upper right of the figure were also taken in the x-z plane corresponding to various depths, z = 0, .5, 1.0, and 1.5 cm in the synthetic fat. The photographs which are double exposures taken both before and after irradiation of the model are oriented so that the deflection to the left is proportional to the temperature as a function of x (vertical direction on photograph). The temperature difference ΔT between superimposed "B" scans (with the same vertical x scale as the "C" scans) is approximately proportional to the absorbed power density distributions and the square of the electric field over the regions scanned, as described in the previous section. Temperature scale corresponds to 2.5° per division. The family of "B" scans in the lower right of the figure were recorded for muscle region. The "B" scan at the lower left of the figure is a scan taken along the z axis of the applicator. Note the discontinuity due to the difference in electrical properties of the two media. The thermograms clearly show that the fat to muscle heating ratio is minimized for b = 13 cm (b = one wavelength in fat) and becomes excessive for aperture heights less than 1/2 wavelength.

2. Spherical Tissue Models Exposed to Various Sources

Fig. 10 illustrates the results of applying the method to the simulated spherical brain structures shown in Fig. 8 [2]. Thermograms at the left of the figures are "C" scans taken over the surface of the separated hemisphere while the thermograms in the middle are "B" scans taken before and after exposure to the microwave sources proportional to the absorbed power along the z axis of the spheres. Thermograms at the right are also "B" scans taken along the x axis of each sphere. The graphs below the "B" scans are comparisons between theoretical and measured absorbed power. The results agree well with the exception of the deviation between the theoretical and experimental values of large spheres exposed to 918 MHz power. This is due to the converging fields of the finite aperture source that was used to irradiate the phantom model at this frequency.

3. Circular Cylindrical Tissues Exposed to Various Sources

Triple-layered circular cylindrical tissue models roughly simulating portions of human thigh and arms, shown in Fig. 8, were exposed to a number of sources [2]. The large cylinder consisted of simulated bone of outside radius 1.9 cm, muscle of outside radius 6.3 cm, and fat of outside radius 8.9 cm. The smaller cylinder, composed of the same materials, had respective interface radii of 0.95, 3.18 and 4.45 cm. Thermographs were taken of the models after they were exposed to a 2450 MHz approximate plane wave source consisting of the far-zone field of a horn antenna in an anechoic chamber. Figs. 11 and 12 illustrate the results in terms of a standard cylindrical coordinate system corresponding to the cylinder geometry. The data on the left side of each figure were taken from a $R - \phi$ plane surface of the cylinder with the incident magnetic field parallel and the electric field perpendicular to the z axis of the cylinder at $\phi = 0°$. The data on the right side of the figure were taken from the $R - z$ plane surface of the cylinder with the incident electric field parallel and the magnetic field perpendicular to the z axis of the cylinder at $\phi = 0°$. The "B" scans for each model were taken in the $R - \phi$ plane along lines corresponding to $\phi = 0°$, 45°, and 90°, as marked on the "C" scans of each left-hand figure. The single "B" scan for the right-hand figure was taken along the R axis in the $\phi = 0$ plane. The temperature information was converted into relative heating patterns expressed by dotted lines and compared to theory as expressed by solid lines in the figures below the "B" scans. The spatial scales are 2 cm/div and the temperature scales are 2.5°C/div. The theoretical results due to Ho, et al [13] show good agreement with the measured relative heating curves. The models were also exposed to other type sources including the direct contact cavity applicator illustrated on the right of Fig 13 operating at 750 and 915 MHz, and a commercial European 433 MHz (12 cm long capacity-loaded dipole) diathermy applicator shown at the left of Fig. 13. The thermographic results from exposing the models to these linearly polarized sources are illustrated in Figs. 15 and 16. The format for each figure is the same as for Figs. 11 and 12, except all "B" scans are limited to the $\phi - 0$ axis. Theoretical curves due to a plane wave source are compared to the experimental results for these cases also. Although the actual sources used were finite in size, the agreement in the results for the exposed left sides of the cylinders are surprisingly close. The patterns clearly show the increased penetration of the fields into the muscle and the decreased field amplitude in the subcutaneous fat as the source frequency is lowered. Reflections from the fat-muscle interface are clear at all frequencies, while reflections from the bone are apparent only at the lower frequencies where penetration is sufficiently deep to produce the visible heating effects.

4. Scale Models of Ellipsoids Simulating Man Exposed to Radio Frequency Sources

It has been shown that when ellipsoidal biological tissue bodies, small compared to a wavelength, are exposed to plane wave fields, the absorbed power density patterns may be obtained from the simple superposition of the internal electric fields obtained from the quasi-static solutions of the electric and magnetic field coupling calculated independently [14],[15]. Thus, the solutions may be used to determine the absorbed power characteristics for any arbitrary combination of electric and magnetic fields as long as the proper relative amplitudes and phases of the incident field components are used when the solutions are superposed. We would expect similar conditions to hold for arbitrary shapes such as a figure of man as long as the body weight is small compared to a wavelength. The major problems for whole body exposure of a phantom man in the HF band are: (1) the phantom model would be excessively large and cumbersome, and (2) the HF power flux densities required to produce thermographically measurable temperature increases would require impracticably high transmitter powers and large antennas. The most logical approach is the use of phantom models of man scaled down in size and exposed to fields scaled up in frequency [16],[17],[18]. This can be accomplished by the use of synthetic tissue material with the same dielectric constant of actual tissue and electrical conductivity and exposure frequency increased by scale factor. The power absorption patterns in the model will then be identical for exposure to the model frequency as those for the full scale model exposed to the modelled frequency, with the exception that the magnitude of the absorption will be increased by the frequency scale factor for the same applied field intensities. This provides an immediate advantage of lower required power. At the wavelength we are concerned with, the externally applied field components have the same effect on the power absorption components whether they originate from a propagating wave or a quasi-static source. Thus, we are free to use any source that will illuminate the model with uniform electric and magnetic components. The resonant cavity provides the most efficient conversion between a given amount of source power to high intensity electric and magnetic field components. Fig. 17 illustrates the phantom scale model of man exposed to the fields in such a resonant cavity. The particular cavity illustrated was designed for TM_{110} and TE_{102} mode resonance at 144 MHz. Each mode can be fed by a separate probe with variable control of the relative phase and amplitude of the power delivered to the feeds. A scale model man or other exposed subject is normally oriented in the center of the cavity at the position of maximum electric field and zero magnetic field for the TM_{110} mode and maximum magnetic field and zero electric field for the TE_{102} mode. The resultant electric and magnetic fields are therefore in space quadrature and independently controllable in phase and amplitude at the position of the exposed model so that any field impedance condition can be simulated, including plane wave conditions. The top of Fig. 18 illustrates the thermographic results of exposing a 4.3 cm diameter sphere to the 144 MHz TM_{110} electric field in the cavity simulating a 51.2 cm diameter sphere of muscle tissue exposed to 24.1 MHz. In this case, the electric field was parallel to the plane of separation along B-B'. The upper left of the figure displays the intensity or "C" scan, the upper right is a profile scan with multiple linear "B" scans across the surface, and a single linear scan taken before and after exposure of the model is shown along the line A-A' on the intensity scan. The resulting double exposure is shown directly below the intensity scan. A similar double scan was taken along line B-B', indicated on the intensity scan and brightened along the profile scan. The results are shown directly below the profile area. The measured power absorption was corrected to the equivalent value for the full scale and normalized for a square rms electric field by 1 V/m by dividing by the square of the cavity field. The experimental and theoretical values of W, calculated for the point indicated by the arrow, is shown under the figures. The radius R, the frequency scale factor sf, and the frequency f, are shown at the top of the figure. The bottom of Fig. 18 illustrates the results of exposing the sphere to the magnetic field with a similar format for the display of the thermographic results. In this case, the absorbed power characteristics are normalized to a magnetic field intensity of 1 A/m.

The intensity and profile scans for the electric field exposure show very little absorbed power, as expected, because of the poor coupling of the electric field to the sphere. Prior to exposure, the temperature of the model sphere was lower than the surrounding styrofoam enclosure. After exposure, the surrounding enclosure was heated more than the synthetic tissue by the external electric fields producing a halo effect, as seen on the intensity and profile scans. The A-A' and B-B' cross-sections of the synthetic tissue, however, closely correspond to that expected by theory. The edges of the spheres are indicated by the white lines on the A-A' and B-B' scans. The exposure of the sphere to the magnetic field perpendicular to the observation plane produced the classical absorption pattern increasing with the square of the distance. Note that the peak value of W = 0.366 W/kg agrees very well with the theoretical value.

Fig. 19 illustrates the results for an ellipsoid simulating a 70 kg man with a/b = 5.0, a = 74.8 cm exposed to the E and H fields. The major axis of the ellipsoid is oriented parallel to the electric field and the magnetic field is perpendicular to the plane of observation. The results match very well with the theoretical distributions predicted by Equations 14-16 in a previous section of this series "Biophysics - Energy Absorption and Distribution." The uniform absorption due to the electric field is more apparent and considerably higher than that of the corresponding spheres (factor of 44). The absorption due to magnetic coupling is changed considerably. It increases rapidly with distance from the major axis and decreases gradually with distance from the minor axis along the periphery.

5. Spheres and Ellipsoids Exposed in Cavities

In a number of investigations on the biological effects of electromagnetic radiation, metallically enclosed cavity-type chambers have been, or are being, used for exposing small animals. The major advantages of this method are: (1) coupling efficiency is high, so only relatively low

power sources are needed, (2) outside radiation is eliminated, preventing interference to other users of the frequency, and (3) dosimetry is partially simplified since with proper cavity design, all of the transmitted power which is easy to measure will be absorbed by the animals.

The major disadvantages of the method, however, are: (1) difficulty in relating the magnitude of the fields in the cavity and associated effects on the animals to the case of human exposure to a plane wave radiation, (2) difficulty in determining the distribution of the absorbed energy among the subjects, and (3) difficulty in determining the distribution of energy between the animals and other absorbent material such as food and water when multiple subjects or objects are present.

Guy and Korbel, [19] have shown that when groups of animals are exposed in cavities, it is extremely difficult to maintain a constant absorbed power relationship in each animal with respect to the power incident to the cavity. The results show variations as great as 1000 to 1 in absorbed power intensity in the animal, depending on its position with the rest of the subjects or its position within the cavity. Contact with metallic walls or standard-type water dispensers can also produce serious problems. Measurements with a standard power density meter sensitive only to electric fields cannot be used to predict the power absorption in a particular animal exposed in the cavity since absorption may also be highly dependent on the magnetic field strength which tends to be maximum in regions where the electric field strength is minimum. When single subjects are exposed in such chambers, however, the total absorbed power in the subject can be easily determined by standard means, as demonstrated by Justesen and King [20], Hunt and Phillips [21].

The technique involves the exposure of a single subject in a high Q cavity such that all of the power entering the cavity is absorbed by the animal, thus, the total absorbed power or the average absorbed power density can be calculated. Unfortunately, this does not give any information on hot spots or peak absorbed power density. The thermographic technique described previously can be used to determine this in phantom models or actual animal bodies providing certain precautions are taken. Models described previously were bisected along lines of symmetry with each half covered with a thin plastic film. Thus, the technique is only applicable to linearly polarized fields where the object can be oriented parallel to the field lines. For arbitrary-type polarization such as existing in cavities or in more general exposure conditions, a different technique has been developed by Guy, et al., [22]. Instead of using a plastic sheet attached to each half of a model, a silk screen layer is stretched very tightly over each half section. Animal tissue matter or modelling material will flow through the openings in the silk screen providing for good adhesion and electrical coupling between the two sections of the model. The models can easily be separated and rejoined repeatedly without loss of adhesion or electrical continuity.

A number of models with the same electrical properties as human or beef muscle, including spheres 6 cm in diameter and 14 cm in diameter, and ellipsoids with axial ratios of 2.1 to 17.2 cm were tested in 2450 MHz and 915 MHz standard microwave ovens using the technique. Each oven was instrumented so that the incident and reflected power at the feed to the oven cavity could be measured during exposure. The intact models were exposed in each oven for 5-60 sec and thermograms of the plane of separation were taken before and after exposure in a manner similar to that described previously. Scans were made of the half-model corresponding to the three major planes of orientation as illustrated in Fig. 20 for the 6 cm diameter spherical model. The coordinate system was defined with the origin at the center of the exposed object such that the x axis was directed toward the front of the oven and the z axis in a vertical direction. Single scans were made over regions of maximum power absorption and along the major axis. The net power to the oven, P_n, and the maximum absorbed power density, W_{max}, as calculated from the thermograms are given in the figures. Since the object was rotated on the z axis on the standard platform in the 918 MHz oven, the patterns in the x-z and y-z planes are identical for that case. Fig. 21 illustrates the patterns for the 14 cm diameter sphere, Fig. 22 for the ellipsoid with the major axis oriented along the x axis, and Fig. 23 for the ellipsoid with the major axis oriented along the y axis. The observed data clearly show the pronounced focusing of the cavity fields in the center of the smaller spheres as observed in past work for spheres exposed to plane waves. The data also show a marked superiority of the 918 MHz oven in terms of power penetration and absorbed power uniformity in the larger objects.

D. WAVEGUIDE EXPOSURE SYSTEMS

A very effective and economical method for exposing small animals or *in vitro* preparations is through the use of a waveguide system where the preparation to be irradiated is placed in the waveguide or transmission line. This method is a marked improvement over a cavity system since the fields applied to the preparation are truly propagating in nature and contain both E and H components. With proper choice of waveguide or transmission line size the fields can be made to closely approximate those of a plane wave. The advantages are: (1) the total absorbed power or average absorbed power density in the exposed subject or specimen can be determined by measuring incident and reflected power at the feed end of the transmission line and the transmitted power at the terminal end of the line with standard instrumentation, (2) measurements of biological signals from the preparation can easily be monitored through properly designed terminals in the walls of the waveguide without interference to the equipment and minimum disturbance of the fields, (3) the environment surrounding the subject, whether liquid or air, can easily be controlled, (4) nutrients can be supplied and waste removed with minimum disturbance of the fields, and (5) a relatively pure field configuration of known characteristics can easily be maintained. Exposure apparatus ranging from large TEM cells for exposing dogs and monkeys [23], [24], medium size TEM cells for rats [25], and small waveguide cells for exposing mice have been used [26]. Additional type systems are described below.

1. In Vitro Preparations

Fig. 24 illustrates a simple waveguide system for exposing small nerve or muscle preparations in vitro [27], [28]. The system consists of a silver-plated S-band WR 284 waveguide equipped with inlet and outlet ports for circulating fluids. The fluid, which usually consists of temperature-controlled mammalian Ringer's solution, serves as an exposure environment for maintaining the viability of a wide spectrum of different in vitro preparations. A temperature-controlled culture medium containing cell cultures could also be used in such a system. The figure depicts a ganglion stretched across the waveguide between a set of stimulating electrodes on the pre-ganglionic side (outside the waveguide) and a suction electrode on the other (with a glass capillary projecting into the waveguide to make contact with the post-ganglion nerve). In some preparations, both the stimulating and the recording electrodes can be placed at opposite sides of the waveguide. A quarter-guide wavelength of matching dielectric with a dielectric constant of 6 can be used to match the incident energy to the Ringer's solution less than 3% of reflected power. The system can be illuminated with either CW or pulsed power sources with incident reflected powers measured by means of a directional coupler and power meter or other methods of power monitoring while various biological tests are made on the specimen. The absorbed power density in the preparation can be calculated by the following formula

$$P = 4\alpha \frac{P_I - P_R}{A} e^{-2\alpha x} \qquad (1)$$

where

- P: absorbed power density in the nerve (W/cc)
- P_I: incident power (W)
- P_R: reflected power (W)
- x: distance between the nerve and the Ringer's solution interface (cm)
- A: cross-sectional area of the waveguide (cm^2)
- $1/\alpha$: depth of field penetration in Ringer's solution (1.78 cm at 2450 MHz)

Absorbed power densities up to 1.5 kW/kg from 100W CW sources, and 220 kW/kg peak power from 10 kW pulse sources can be produced in the specimen using an S-band waveguide at 2450 MHz.

2. An Improved Waveguide System for Chronic Exposure of Intact Animals

The major disadvantages of most waveguide exposure systems and, for that matter, free field or plane wave exposure systems for illuminating normal living animals is that the total absorbed power by the animal can vary over a wide range depending on the position and movement of the animal. Thus, it is extremely difficult to maintain a match between the generator and the exposure chamber. Of course, circulators or isolators may be used with the system to eliminate the reflections, but the widely fluctuating absorption characteristics of the animal remains as a serious problem. With increasing evidence that long-term chronic exposures of biological systems to low level electromagnetic fields will produce effects that cannot be produced by short-term exposures at much higher levels of field strength, there has been considerable interest in exposure systems for exposing a population of animals for long periods of time. Plane wave exposure systems and cavity systems are not very useful for this situation due to the problems that have been discussed above. Guy, et al., [29] have developed an inexpensive method for exposing a population of animals to a single source while unrestrained and living under normal laboratory conditions with access to food and water and efficient waste removal without disturbing the field conditions. The system consists of a number of individual exposure cells connected through a power divider network to a single power source. Each cell consists of a section of circular waveguide constructed of galvanized wire screen of .63 cm square mesh, as shown in Fig. 25. At each end of the guide are identical, readily removable, and compact transducers for converting TEM fields at coaxial cable inputs to either right- or left-hand circularly polarized TE_{11} mode fields in the cylindrical waveguide. The assembled cell consists of a four-terminal device with two terminals at each end. Power fed into the coaxial terminal, R_F, at the feed transducer will launch a right-hand circularly polarized wave which will propagate down the guide and couple to the coaxial terminal, R_L, at the load end. Similarly, the power fed to the terminal, L_F, will launch a left-hand circularly polarized wave which couples to the terminal, L_L, at the load end. In an unloaded cell, there will be no cross-coupling between the R and L terminals.

During operation of the system, a rodent housed in a plastic chamber of adequate size for normal living conditions is placed in each cell. Each animal may move freely around in the chamber with very little change in power coupling characteristics. The incident circularly polarized wave insures that the animal is uniformly illuminated with a propagating field (not unlike a radiation field), regardless of his orientation and movements. The severe changes in coupling due to animal orientation with respect to field polarization observed for plane wave exposure systems are virtually eliminated. When power is fed to terminal, R_F, reflections from the animal arrive at the feed transducer chiefly as a circularly polarized wave at the opposite sense of rotation, thereby coupling to the other terminal, L_F. Power transmitted beyond the animal remains in the same sense of circular polarization so most of it is coupled to the terminal, R_L, at the load with a negligible amount coupled to the other, L_L, terminal. Laboratory measurements indicate that the input VSWR rarely exceeds 1.5 and never exceeds 1.8 at the input terminal, R_F, of a cell loaded with a freely moving rat, regardless of the position of the animal. Furthermore, the transmitted power to the L_L terminal at the load end rarely exceeds 0.1 of that transmitted to the R_L terminal. Thus, for a given incident power level to

the cell, the approximate total power coupled to the animal can easily be determined by subtracting that measured at terminals L_2 and R_1 of the cell from the total. If greater accuracy is desired, the small reflections to terminal R_F and power coupled to terminal L_1 can also be subtracted. The absorbed power density distributions can be measured in phantom models of a test animal exposed in the system using a thermographic technique. Tests made on ellipsoidal phantom models of a 333 gm rat exposed in various possible shapes and positions in a 20 cm diameter exposure chamber operating at 918 MHz indicated that the subjects absorbed approximately one-quarter of the input power to the cell, regardless of position. Based on 1 W input (average incident power density of 3 mW/cm^2) the average absorbed power density varied from 0.47 to 0.6 W/kg and the peak absorbed power density varied from 0.7 to 1.15 W/kg in the phantoms. A low-cost 700 W microwave source can be used with the system to expose as many as 200 animals to a power density as high as 10 mW/cm^2. The maximum available power density could be increased inversely with the number of subjects to approximately 2 W/cm^2 for a single subject which would allow short-term exposures to be made for dosimetry purposes. Water may be supplied to the animal via a standard water bottle and glass tube arrangement. Currents due to the contact of the animal with the water supply are eliminated by a quarter-wavelength choke decoupler surrounding the water tube at the point of entry into the chamber. Dry food pellets can be supplied through the chamber by means of a special dispenser and waste materials can be allowed to drop out of the chamber through special plastic funnels and portholes.

E. ABSORBED POWER DISTRIBUTION IN ANIMALS AND MAN EXPOSED TO VARIOUS ELECTROMAGNETIC SOURCES

1. Rabbit Head Exposed to 2450 MHz Diathermy "C" Director

The absorbed power distribution along the anterio-posterior axis of the eye and extending to the head of a rabbit exposed to a microwave diathermy "C" director was determined by use of the thermocouple micropipette technique described in Section B-2. The animals were exposed to the near-zone of the applicator with horizontal polarization and the distance between the crossing point of the dipole feed and corneal surface of the eye set to 5 cm. Incident power density at the same position as the right eye of the rabbit was measured with a Narda 8100 electromagnetic radiation monitor with the animal absent. The absorbed power density patterns for five animals are shown in Fig. 26. In all cases, the absorption reached peak values within the vitreous body about 1.5 cm behind the cornea, with a mean value of .92 W/kg based on a normalized 1 mW/cm^2 incident power level.

2. Rabbit Head Exposed to 2450 MHz Resonant Slot Antenna

Power deposition patterns based on measurements made in four albino rabbits exposed to a horizontal resonant slot antenna (the ground plane large with respect to the head of the animal) are shown in Fig. 27. The solid curve corresponds to the mean, whereas, the shaded portion shows the standard error of the mean. Spacing between the slot and the rabbit was set 5 cm with the measurements made in the same manner as that described in the above section. The curves illustrate the absorbed power density in W/kg per watt input to the slot.

3. Rabbit Exposed to Approximate Plane Wave Field

Fig. 28 illustrates the power absorption density pattern measured in a rabbit exposed to 2450 MHz fields normalized for 1 mW/cm^2 as measured along the body axis of the rabbit. The rabbit was illuminated over the dorsal body surface by standard gain horn spaced 100 cm away with the electric field polarized along the axis of the body. Thermograms taken on the rabbit by the techniques described previously were processed by computer and isopower absorption lines were plotted as shown in the figure. Power absorption measurements were measured along the anterio-posterior axis of the eye by the thermocouple micropipette technique. Measurements were taken for the illumination of the dorsal surface parallel to the long axis and also with illumination of the right lateral surface, with E perpendicular to the long axis, as shown in Fig. 29. These measurements agree reasonably well with the thermographic measurements.

4. Cat Exposed to 918 MHz Aperture Source

Fig. 30 illustrates thermographic recordings taken to assess the absorbed power density in actual cat head and a 6 cm diameter phantom spherical model of the head. Thermograms were taken for exposure of the head to a 918 MHz 13 X 13 cm aperture source spaced the distance 8 cm from the dorsal surface. The results clearly show the presence of high absorption areas or hot spots in the head of the exposed cat predicted from the theoretical calculations for a sphere. Both the theory and the measurements indicate approximately 0.8 W/kg peak absorbed power density per mW/cm^2 incident power density. Fig. 31 illustrates measured absorbed power patterns in the head of the cat and the phantom sphere by different methods as a function of distance from the top of the exposed surface. The values are based on a 1 W input power to the 918 MHz aperture source under the same exposure conditions described for the previous figures. The curves illustrate thermograms taken on a phantom sphere and the center of the dead brain. They also illustrate thermocouple and micropipette measurements at the center and off-center of the live brain, as well as the microwave diode measurements made at the surface of the dead brain.

5. Rat Exposed to 918 MHz Aperture Source

Fig. 32 illustrates the thermograph of a study made on a phantom tissue model of the body of a rat exposed to 918 MHz 13 X 13 cm aperture source spaced 8 cm away from the animal. The results clearly illustrate unpredictable absorption peaks that may occur in the body and tail of the rat. The profound absorption 8.6 W/kg at the base of the tail is due to the increased current density resulting from the sharp change in tissue cross-section. The low absorption in the pelvic area is

probably due to a standing wave null resulting from body resonance conditions since the rat model is approximately one wavelength long. Results indicate that one must be extremely careful in drawing conclusions from temperature measurements made with rectal thermometers. Also, one cannot make the easy assumption that keeping the tail or any portion of the rat out from the direct beam of radiation will insure non-exposure and, consequently, no absorption.

6. Phantom Man Exposed to Simulated RF Fields

Fig. 33 illustrates thermograms taken for a scale model man exposed to an electric field oriented parallel to the long axis simulating a 1.74 m high 70 kg man exposed to a simulated 31 MHz electric field in the cavity described in Section C-4. Single profile scans were taken through regions of intensive absorption. The edges of the man for each scan are indicated by white vertical lines. The arrow indicates the position in which the peak absorbed power density was calculated. Areas of maximum absorption occur in the smaller cross-sections of the body such as the knees, ankles and the neck. Note that the maximum absorption at 134 μW/kg for a 1 V/m incident field is more than three orders of magnitude higher than that of an equivalent volume sphere and approximately two orders of magnitude greater than that for an equivalent volume ellipsoid, illustrated previously in Fig. 19. The high absorption in the narrow cross-sections of the body is due to the constriction of the induced current along the length of the body, thereby increasing the current density and electric fields in those areas. The arms are not affected since they are parallel to the large cross-section trunk which shunts most of the induced currents. Fig. 34 illustrates thermographs taken for the same man exposed to a magnetic field perpendicular to the frontal plane simulating a 31 MHz exposure. For this case, circulating eddy currents are produced. There is generally high absorption along the sides of the body in the area of the ribs of approximately 2.52 W/kg for 1 A/m incident magnetic field intensity. Peak absorption occurs in regions where the flow of the circulating eddy currents are forced into the smaller cross-sectional areas or are diverted by severe angular changes of the tissue such as the region near the axilla and the perineum. Since the maximum power absorption due to the electric field exposure occurs where there is minimal power exposure due to the magnetic field exposure, we can predict maximum power absorption density for a plane wave field from the values given in the previous two figures. Except for a change in magnitude, the resulting patterns are identical to those which would occur in actual full scale subjects with homogeneous dielectric tissue composition exposed to fields at any frequency below those indicated. Thus, the results can be extrapolated down to cover the entire RF frequency range, the low frequency range, and even VLF and ELF frequencies. At lower frequencies, however, the nerve and muscle tissues can become anisotropic requiring a much more sophisticated model.

F. LOCALIZED POWER ABSORPTION DUE TO ATTACHED INSTRUMENTATION AND IMPLANTS

When conducting objects, wires, or electrodes are brought in contact with or are implanted in biological tissues exposed to EM fields, high intensity fields may be induced locally where the conductors come in contact with the tissues. These fields can be many orders of magnitude greater than the fields that would normally be present without the presence of the conductors. This is clearly illustrated by Fig. 35 showing thermograms taken of the head of the cat exposed to 918 MHz microwaves, both with and without the presence of a metal electrode inserted in the brain.

With proper electrode design using conductors with electrical conductivity close to tissue some of these problems may be avoided. The use of so-called "transparent leads" used for the leads of EM hazard survey meters in most cases will not eliminate this problem even though they do not disturb the applied field since even weak currents induced in the conductors can produce high current densities at a point of contact with tissue if the contacting area is small.

Fig. 36 illustrates some of the various situations one may encounter and some simplistic models to provide a first order analytical determination of the field enhancements that may occur in the tissues due to the presence of conductors. The figure illustrates tissue bodies of dielectric constant ϵ_t^* exposed to EM fields with an electric field intensity E_o. Fig. 36-a illustrates field enhancement due to wires connecting external instrumentation to electrodes in contact with tissues. Fig. 36-b illustrates field enhancements due to implanted encapsulated instrumentation such as used for pacemakers or for telemetering biological information from the body of the subject. Fig. 36-c illustrates the field enhancement due to implanted conductors such as surgical pins, prosthetic joints and conducting electrodes. For all these cases, currents will be induced in the conductor portions of the instrumentation or implants resulting in field enhancement and an increased absorbed power density, W_e, usually much greater than the normal absorbed power density, W. The value of W_e will, in general, increase with the length, L, of the leads or the implant. An insight as to the severity of the problem can be gained by considering some equivalent configurations more amenable to analysis. For example, the external leads may be represented by a cylindrical conductor as shown in Fig. 36-d, and the internal insulated implant represented by the implanted coaxial antenna shown in Fig. 36-e. A radius, a, and a length, L, is assumed for the conducting portion of each antenna and an insulation radius of b, and dielectric constant ϵ_d is assumed for the implanted coaxial antenna. Each of these cases can be analyzed in terms of the equivalent circuit shown in Fig. 36-f where an equivalent generator with open current voltage equal to the product of the effective length of the antenna and the electric field strength in the direction parallel to the antenna is shown. Z_a and Z_e represent the source and electrode impedances of the antenna, and I_e is the electrode current. If we assume that the contact of the conductor with the tissue in each case is hemispherical with uniform current density, J_e, normal to its surface we have

$$J_e = I_e/2\pi a^2 \qquad (2)$$

The factors of increase of current density, J, electric field E, and power absorption density W normally present in the undisturbed tissue due to the presence of the electrode would be related by $J_e/J = E_e/E = (W_e/W)^{1/2}$ where subscript e denotes values of each quantity at the tip of the implant. If we consider a conducting ellipsoidal shaped implant with dielectric constant ϵ_s^* and major and minor axes 2a and 2b small compared to a wavelength in the tissue, as shown in Fig. 36-c, we may use equations 10-12 previously discussed by Guy in this Lecture Series "Biophysics - Energy Absorption and Distribution" Section E, to predict the increase in field intensity and absorbed power at the tip as a function of b/a and dielectric constant of the implant. Fig. 37 illustrates the increase in field intensity for various materials implanted in muscle with dielectric properties as shown. With dielectric constants or conductivities large compared to that of tissue (muscle at a frequency of 2450 MHz) the minimum factor of enhancement would be 3 with b/a = corresponding to the sphere, and the maximum would depend on the implant material with values as high as 10^7 for copper, 10^4 for carbon, and 13 for the teflon-carbon polymer. The latter material is used for fabricating transparent leads for EM hazard meters and instrumentation used in the presence of EM fields. The nearer the properties of the object are to those of the tissue, the closer the enhancement factor is to unity. When the object is appreciable in size compared to a wavelength, the analysis is much more complex, but we would expect similar degrees of enhancement as predicted for the quasi-static analysis.

The enhancement due to an externally applied cylindrical lead shown in Fig. 36-d can easily be calculated from antenna equations. For a thin rod antenna, short compared to a wavelength, we can obtain the approximate expressions

$$L_{eff} = L/2,\ Z_a = (j2\pi fC)^{-1},\ C = 2\pi\epsilon_o L/\ln(\frac{2L}{a\sqrt{3}}),\ \text{and } Z_e = 4\pi\epsilon_m^* a.$$

Since $|Z_a| >> |Z_e|$, the magnitude of the current is

$$I = \frac{E_o L/2}{|Z_a|} = \frac{2\pi^2 E_o L^2 \epsilon_o f}{\ln(\frac{2L}{a\sqrt{3}})} \tag{3}$$

and the enhanced field is

$$E_e = \frac{I}{2\pi a^2 \sigma_m} = \left[\frac{\pi E_o \epsilon_o f}{\sigma_m \ln\left(\frac{2L}{a\sqrt{3}}\right)}\right] (\frac{L}{a})^2 \tag{4}$$

whereas the field in the tissue based on continuity of the displacement vecter across the air-tissue interface would be

$$E = E_o/|\epsilon_m^*|$$

so the factor of field enhancement is

$$\frac{E_e}{E} = \left[\frac{\pi\epsilon_o|\epsilon_m^*|f}{\sigma_m \ln(\frac{2L}{a\sqrt{3}})}\right] (\frac{L}{a})^2 \tag{5}$$

or for muscle tissue at 2450 MHz with $\epsilon_m' = 47$ and $\sigma_m = 2.21\ \frac{mho}{m}$

$$\frac{E_e}{E} = 1.53\ (\frac{L}{a})^2/\ln(\frac{2L}{a\sqrt{3}}) \tag{6}$$

Thus, with L/a = 100, $E_e/E = 3222$ and $W_e/W = 10^7$ corresponding to a large field intensification at the point of contact. For longer antennas the impedance Z_a would be less, and I would be greater, resulting in an even greater intensification of the field.

For an implanted insulated antenna, short compared to a wavelength, shown in Fig. 36-e,

$L_{eff} = L/2$ and $Z_a \simeq (j2\pi fC)^{-1}$

where

$$C = \frac{2\pi\epsilon_o\epsilon_d L}{\ln(b/a)} \tag{7}$$

and ϵ_d = the dielectric constant of the insulation. For this case, we obtain

$$\frac{E_e}{E} = \left[\frac{\pi f \varepsilon_o \varepsilon_d}{\sigma_m \ln(b/a)}\right] \left(\frac{L}{a}\right)^2 \qquad (8)$$

or for $\varepsilon_d = 2.25$ and $b/a = 2$

$$\frac{E_e}{E} = 10^{-1} \left(\frac{L}{a}\right)^2 \qquad (9)$$

When L/a is typically in the range 10 to 100, $E_e/E = 10^2$ to 10^3, and $W_e/W = 10^4$ to 10^6 indicating that significant field enhancements can occur even for implanted insulated conductors. Note, however, that for implanted insulated leads, the field enhancement will markedly decrease with frequency. For example, $E_e/E = 10$ and $W_e/W = 100$ at 24.5 MHz. Below 2.45 MHz no field enhancements would occur except that due to the portion of the conducting electrode in contact with the tissue, as predicted by Fig. 37. This is not the case for the implanted uninsulated conductor or external lead, however. The latter is not improved significantly for lower frequencies since that product $|\varepsilon_m^* f|$ in Equation (5) remains relatively constant with frequency.

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Research was conducted according to the principles enunciated in the "Guide for Laboratory Animal Facilities and Care" prepared by the National Academy of Sciences National Research Council.

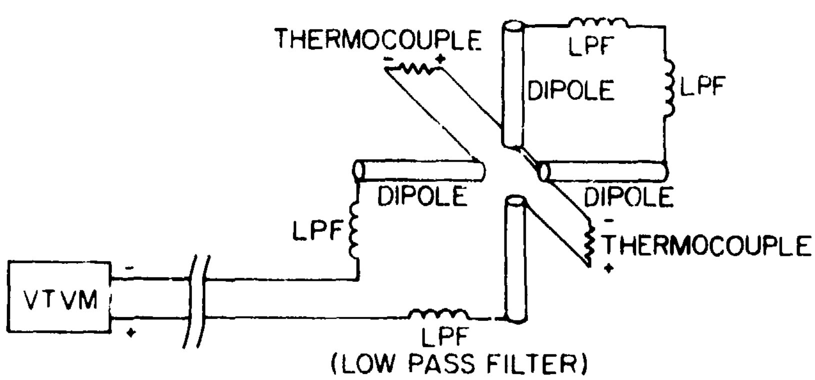


Fig. 1. Simplified sketch of thermocouple survey meter design. (from Johnson and Guy [11])

Fig. 2. Narda Model 8100 radiation survey meter with probes of various scnsitivites.

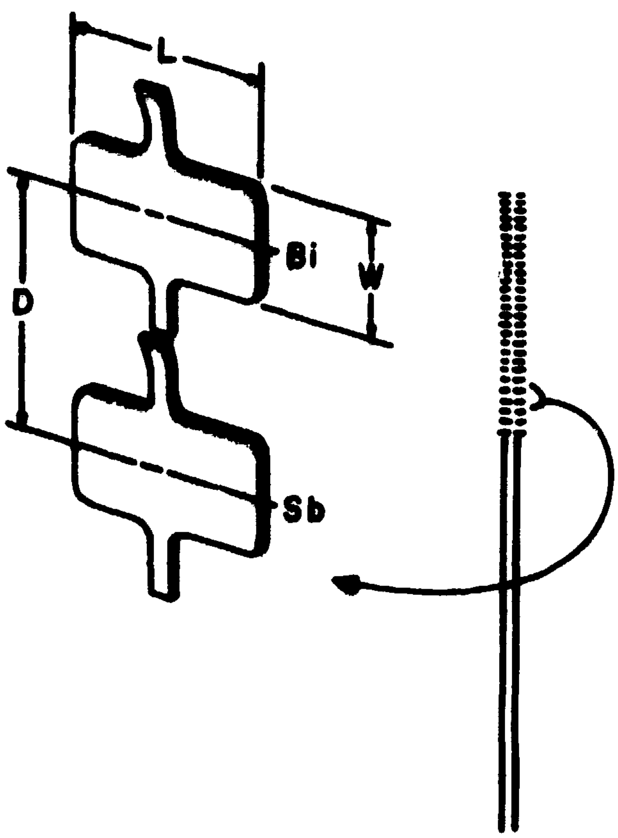


Fig. 3. The Aslan antimony - bismuth broadband field sensor element with distributed thin-film resistive thermo couples.

Fig. 4. Narda Model 8300 Series omni directional broadband radiation survey meters.

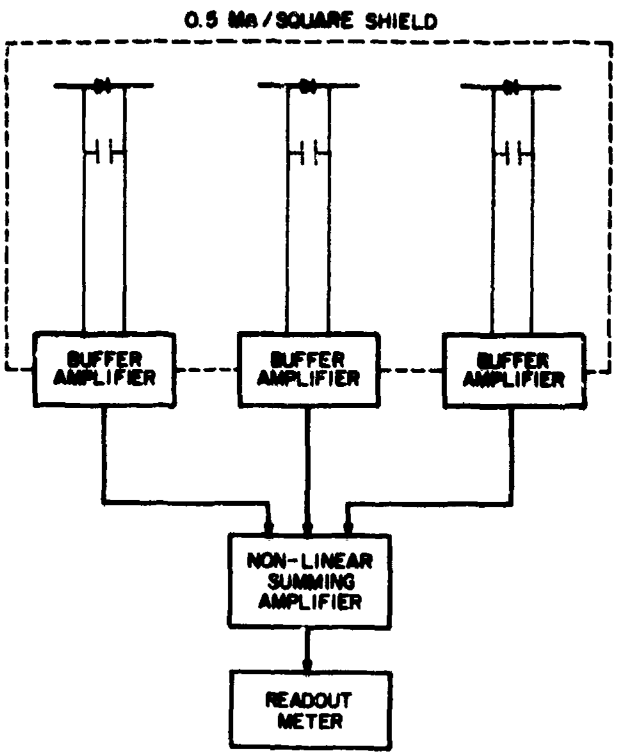


Fig. 5. The block diagram of the Bowman radiation survey meter. (from Bowman [6])

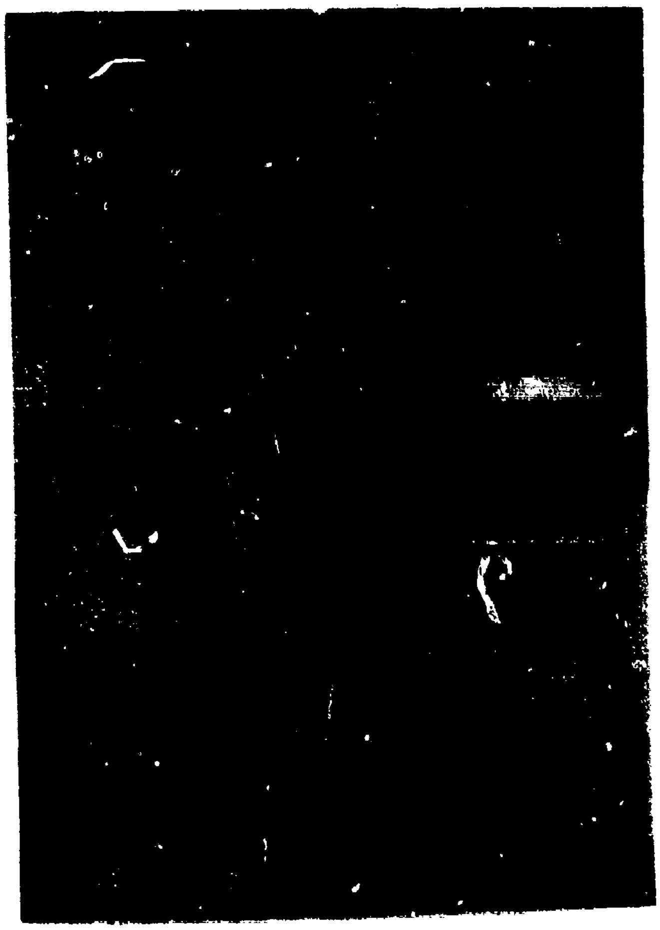
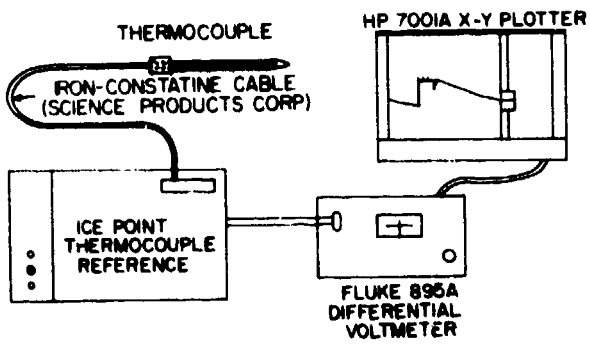


Fig. 6. Bowman radiation survey meter. (from Bowman [6])



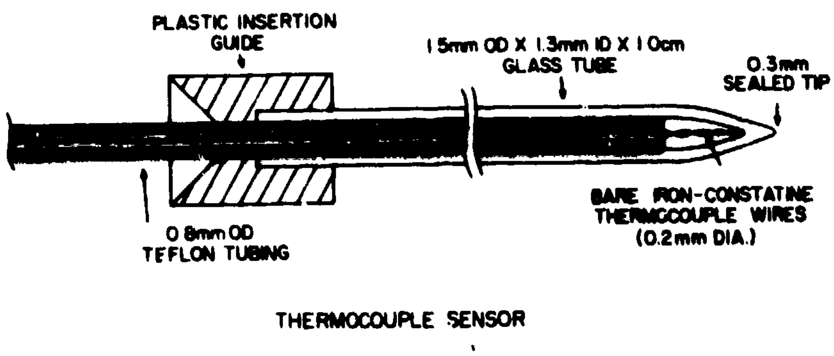


Fig. 7. Apparatus used for determining power absorption density in biological tissue by a thermocouple. (from Guy [2])

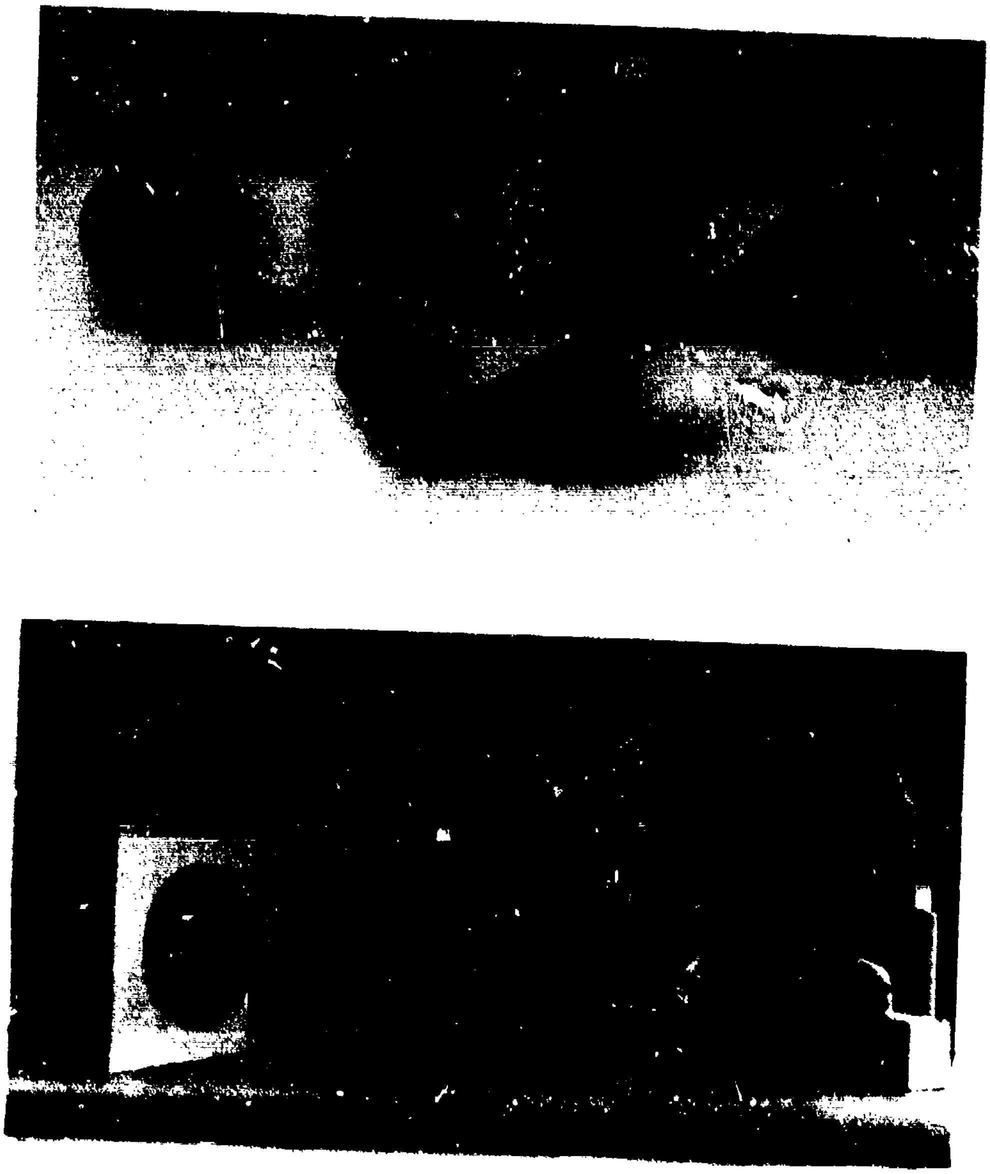


Fig. 8. Phantom tissue models.
(from Guy [2])

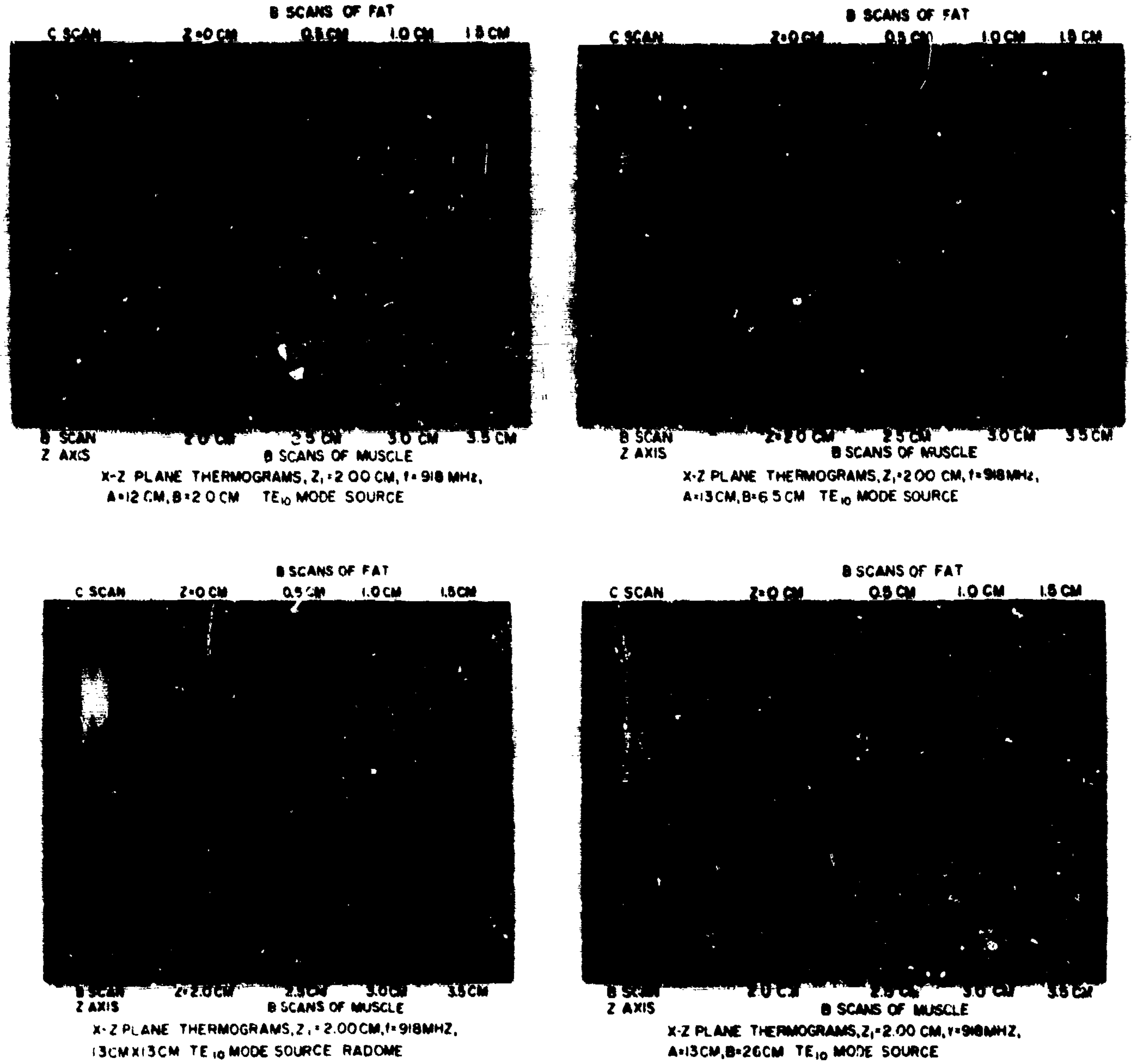


Fig. 9. Temperature distribution patterns obtained by thermography in plane layers of simulated fat and muscle exposed to a waveguide source of electromagnetic fields. (from Johnson and Guy [11])

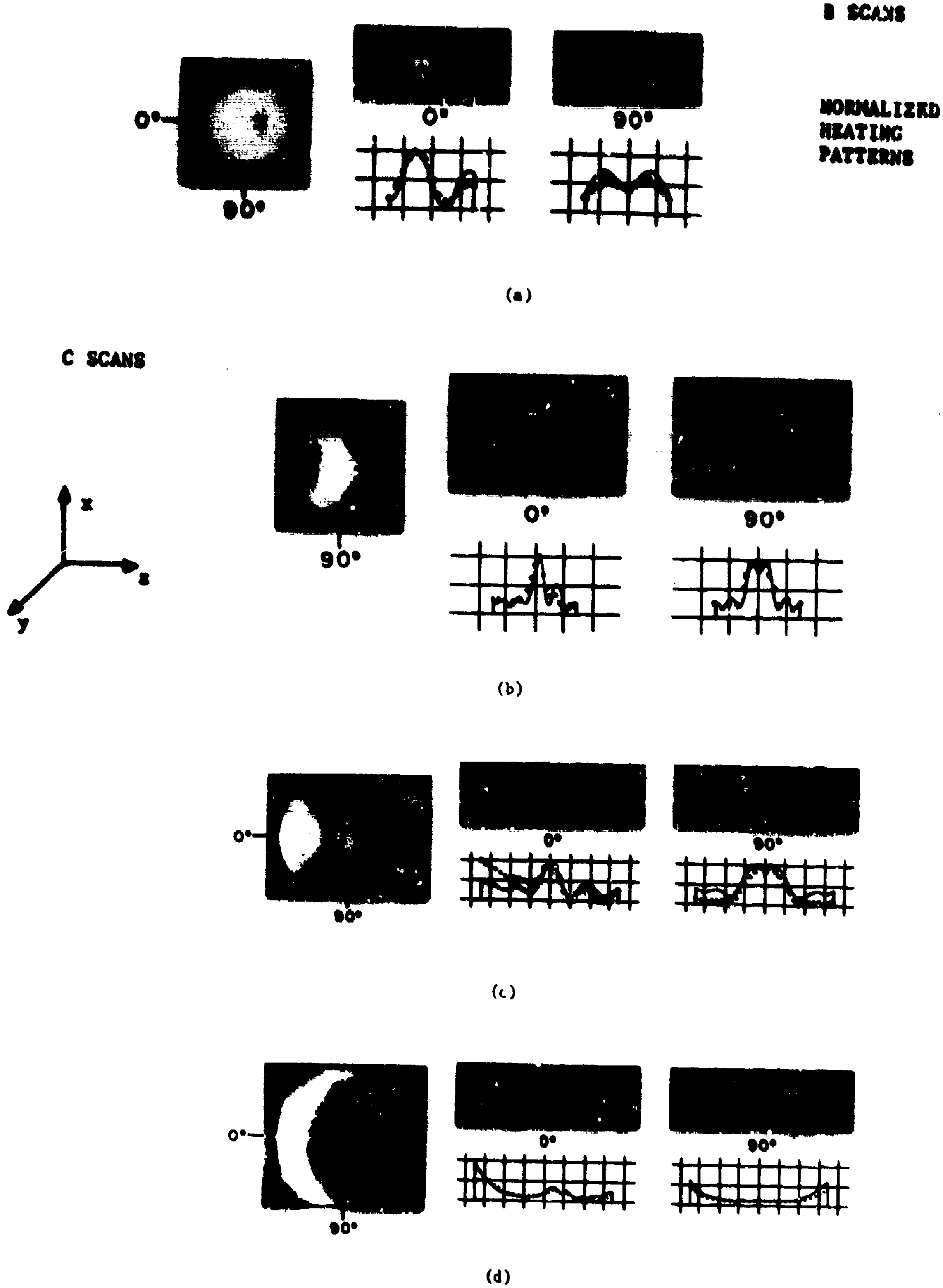


Fig. 10. Thermograms of phantom brain tissue. Scale: C scans, 1 div = 2 cm; B scans, 1 horizontal div = 2 cm, 1 vertical div = 2.5°C; and normalized patterns, 1 horizontal div = 2 cm. (Propagation in z direction with E field polarized along x axis of indicated coordinates). (a) 6 cm diam, 918 MHz. (b) 6 cm diam, 2450 MHz. (c) 14 cm diam, 918 MHz. (d) 14 cm diam, 2450 MHz. ———, plane wave theory; ·····, experimental plane wave; ΔΔΔΔΔ, experimental aperture source. (from Johnson and Guy [11])

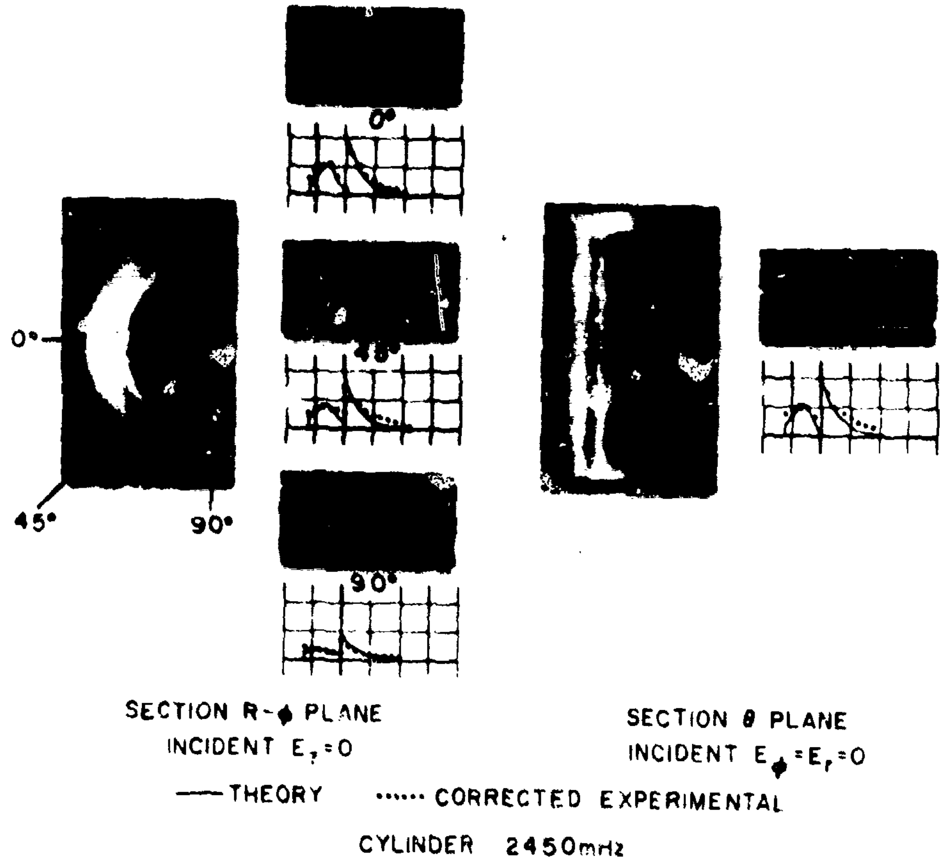


Fig. 11. Thermograms for large-diameter cylindrical phantom tissue model exposed to 2450 MHz approximate plane wave source. (from Guy [10])

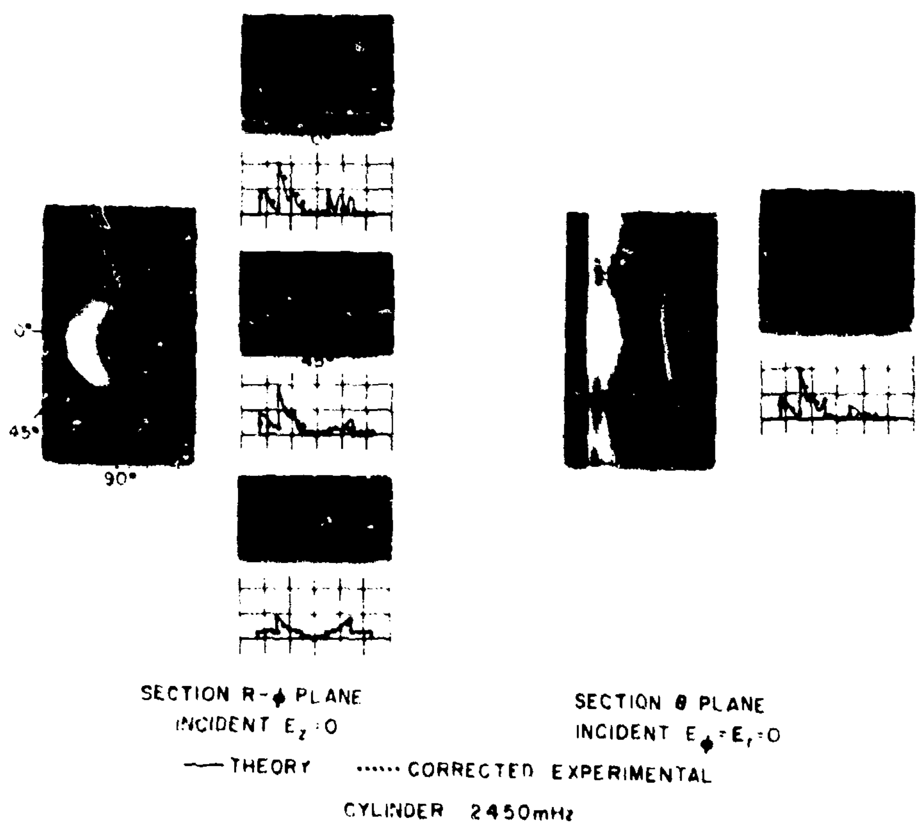


Fig. 12. Thermograms for small-diameter cylindrical phantom tissue model exposed to 2450 MHz approximate plane wave source. (from Guy [10])

Fig. 13. Planar phantom tissue models and aperture sources. (from Guy [10])

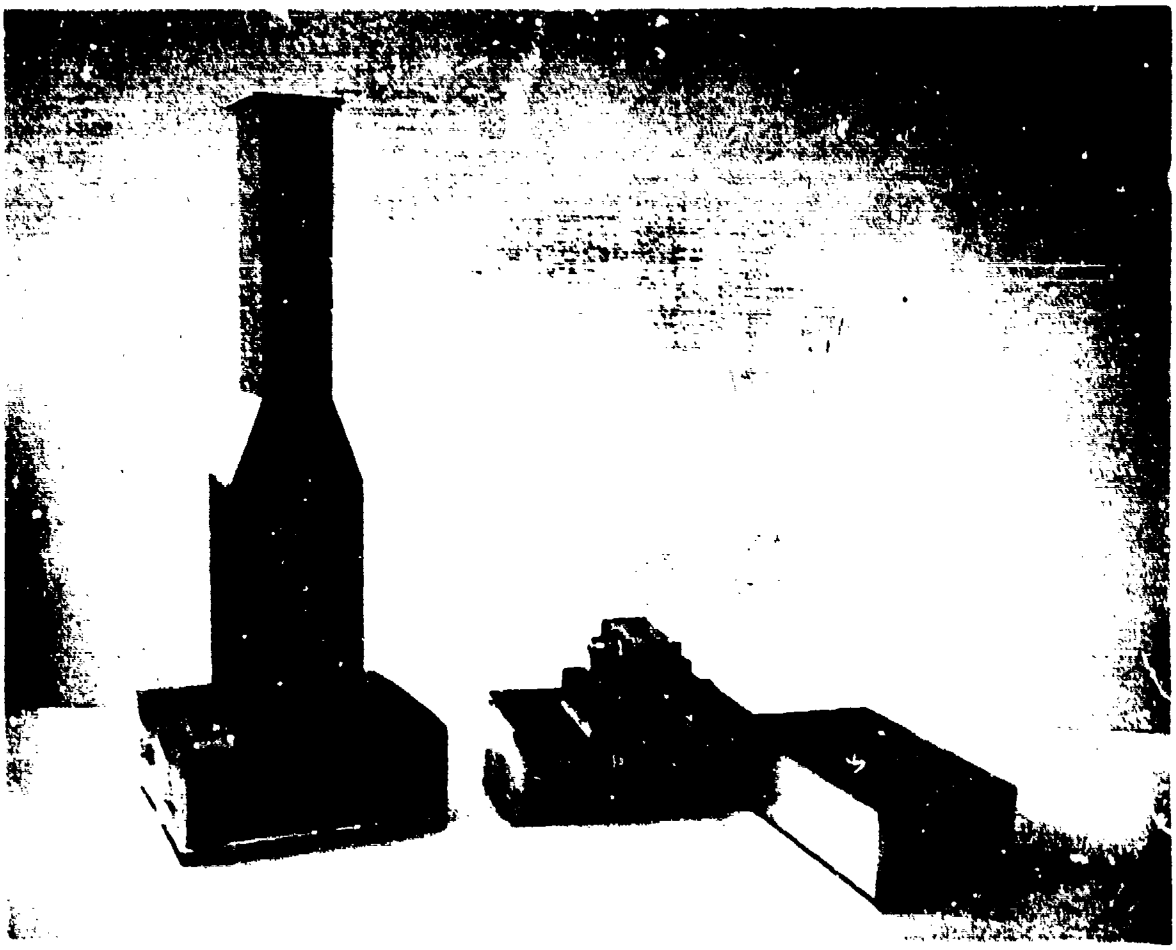
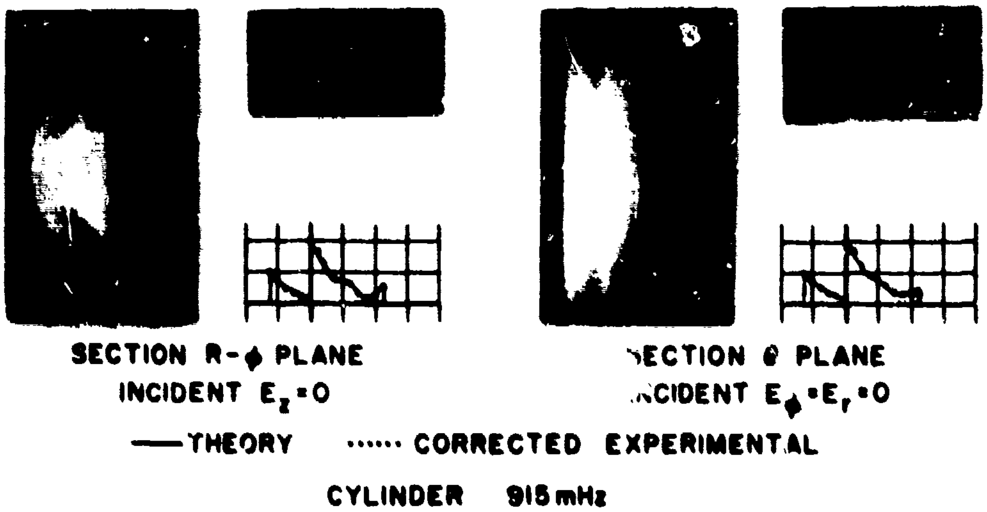
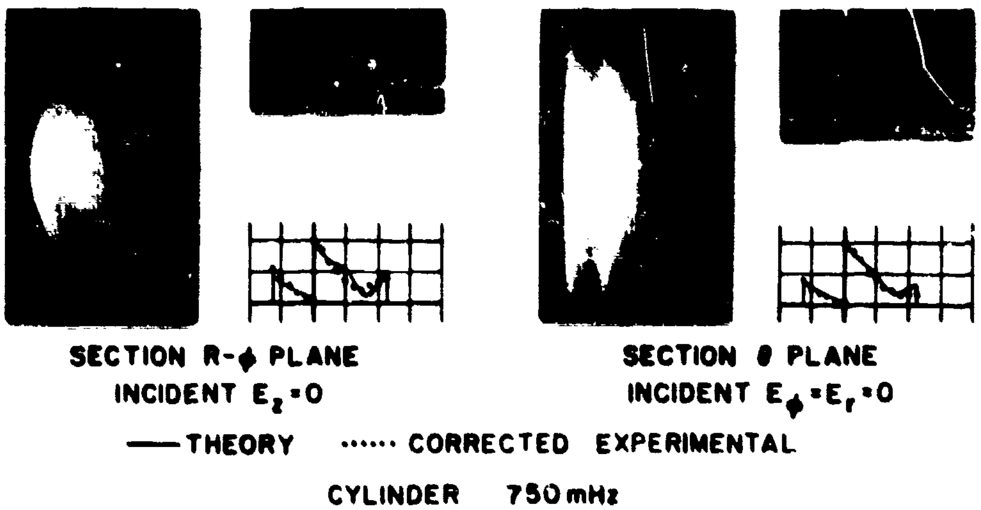


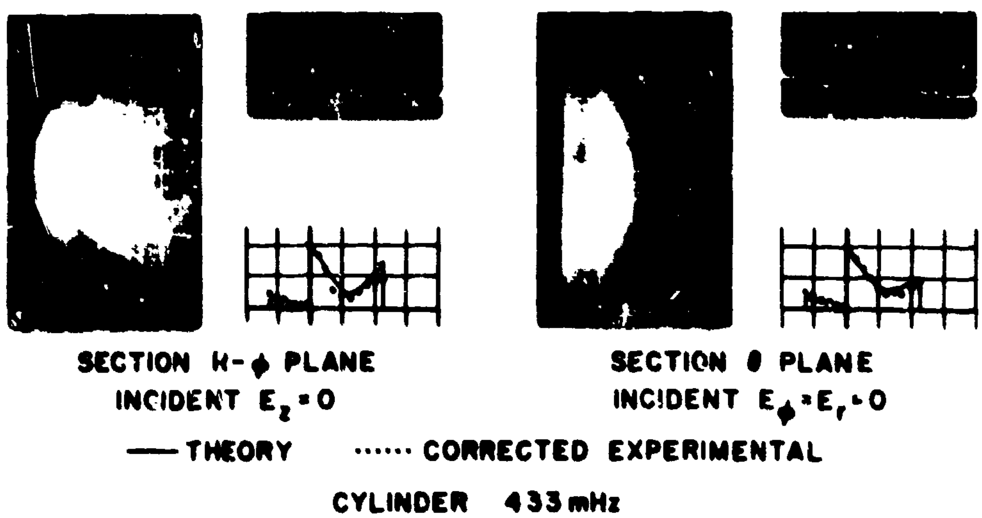
Fig. 14. Various phantom tissue models and electromagnetic diathermy sources. (from Guy [10])



Large cylinder exposed to 915 MHz 12- by 16- cm cavity-aperture source. (Power: 180 W for 40 s).

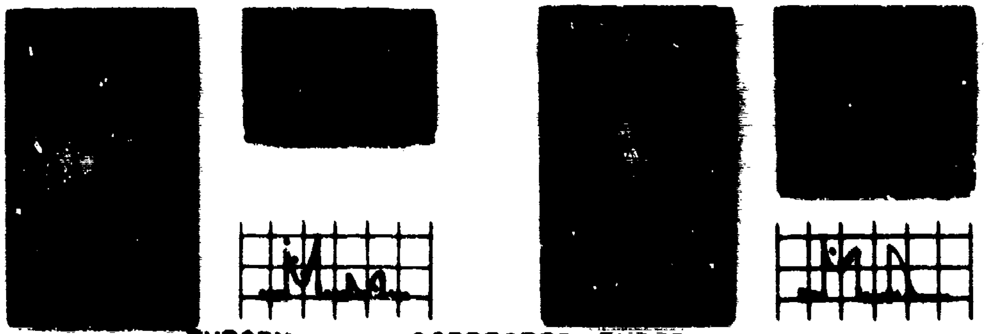


Large cylinder exposed to 750 MHz 12- by 16- cm cavity-aperture source. (Power: 190 W for 40 s).

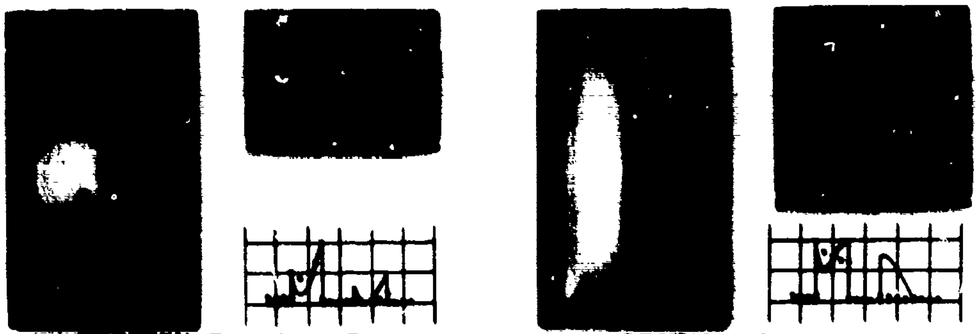


Large cylinder exposed to 433 MHz dipole diathermy applicator. (Power: 210 W for 40 s).

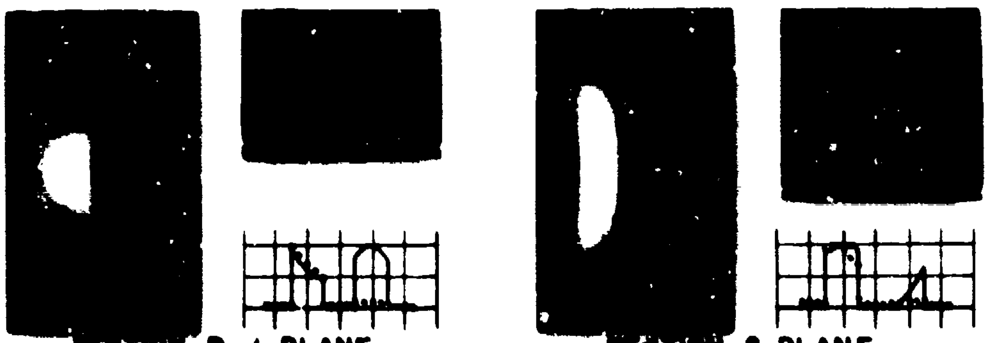
Fig. 15



Small cylinder exposed to 915 MHz 12- by 16- cm cavity-aperture source. (Power: 180 W for 40 s).



Small cylinder exposed to 750 MHz 12- by 16- cm cavity-aperture source. (Power: 190 W for 40 s).



Small cylinder exposed to 433 MHz dipole diathermy applicator. (Power: 210 W for 40 s).

Fig. 16

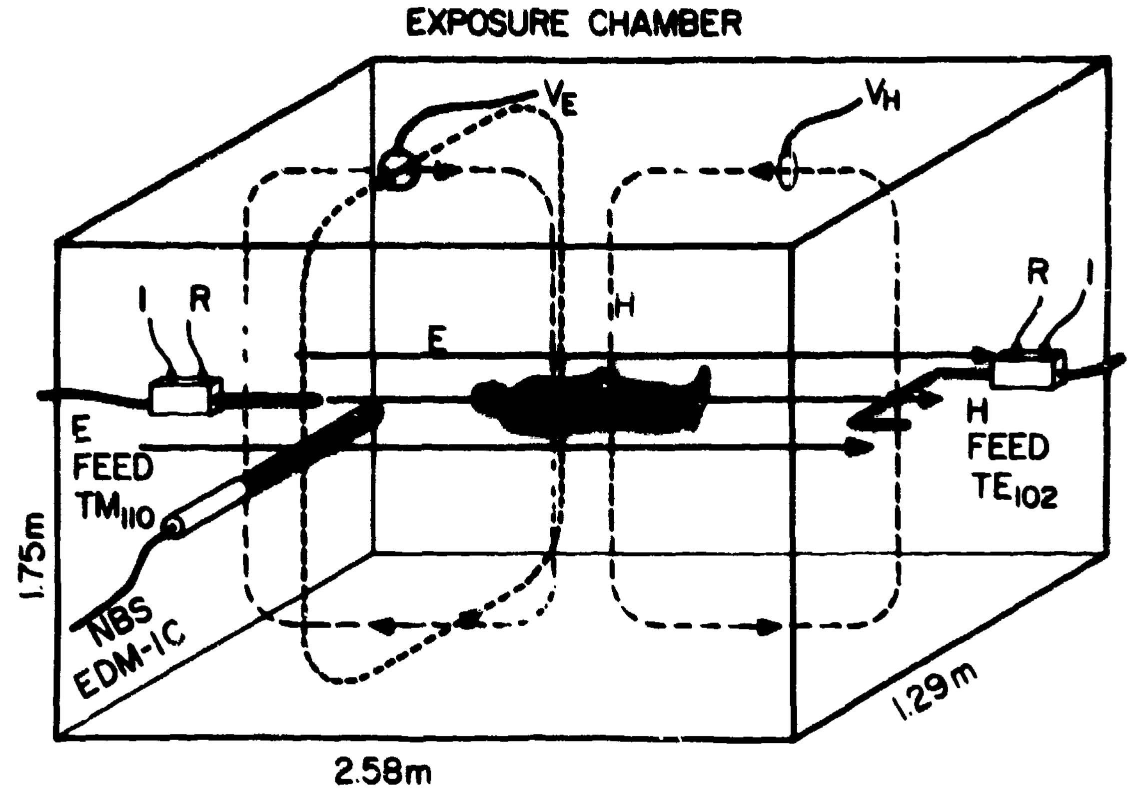


Fig. 17. VHF cavity exposure of phantom scale model of man.

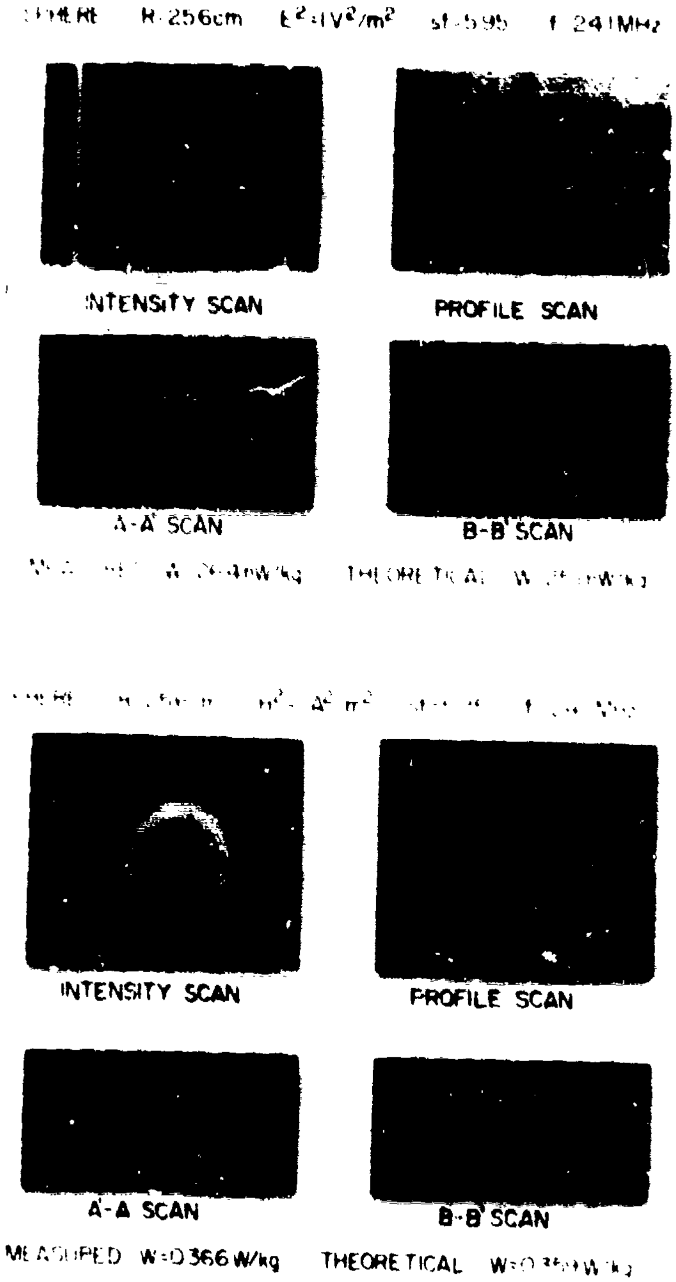


Fig. 18. Scale model thermograms and calculated peak absorbed power density for 70 kg sphere exposed to 24.1 MHz fields: Vert. div = 2°C; Hor. div = 2 cm.

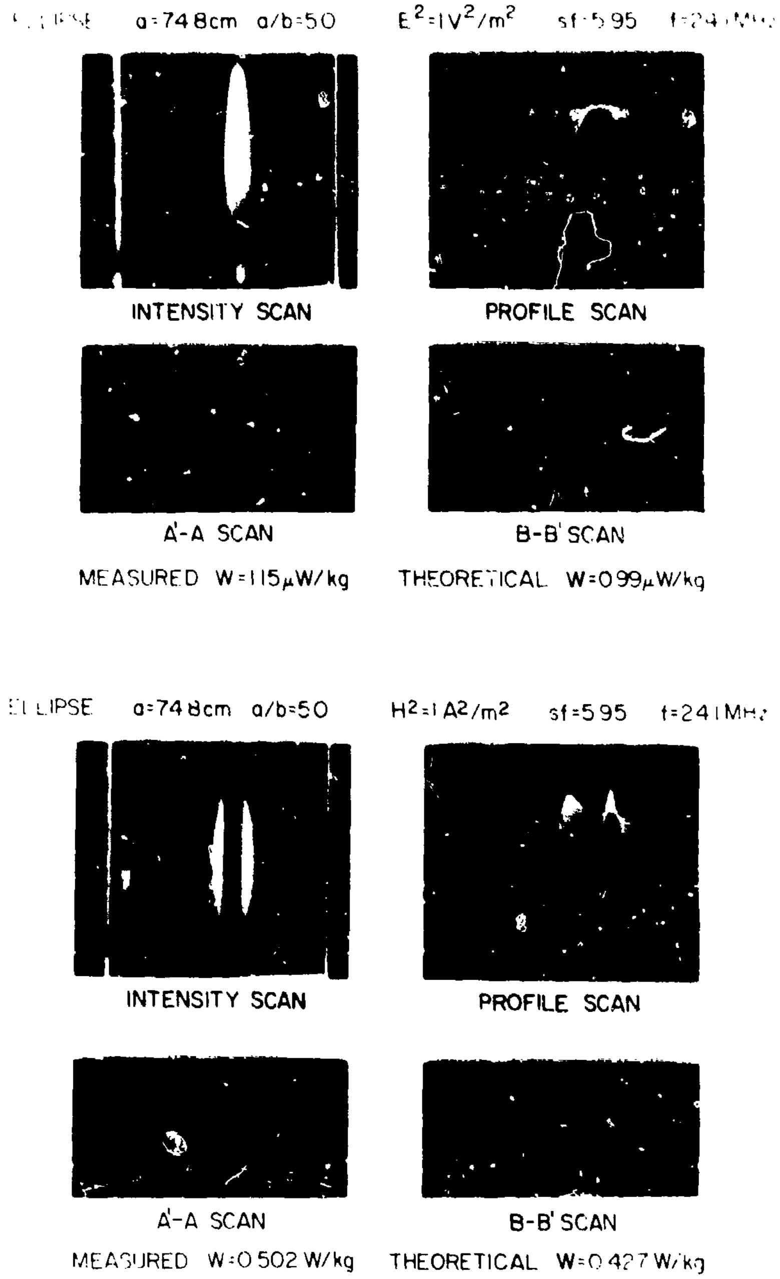


Fig. 19. Scale model thermograms and calculated peak absorbed power density for 70 kg 5/1 ellipsoid (a = 74.8 cm) exposed to 24.1 MHz fields: Vert. div = 2°C; Hor. div = 2.65 cm.

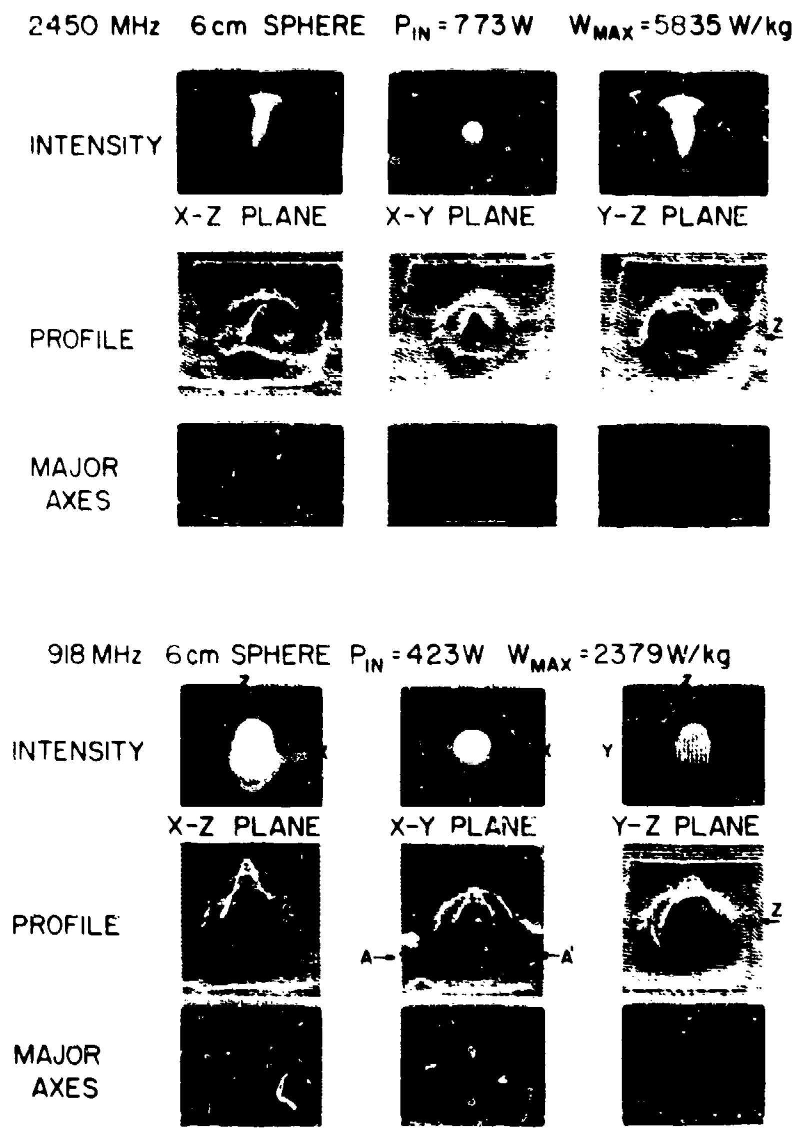


Fig. 20. Thermograms illustrating power absorption patterns for 6 cm diameter sphere exposed in 2450 MHz and 918 MHz microwave ovens. Scale: horizontal - 1 div = 2 cm; vertical - 1 div = 3.33°C; vertical lines on major scans indicate boundaries of object.

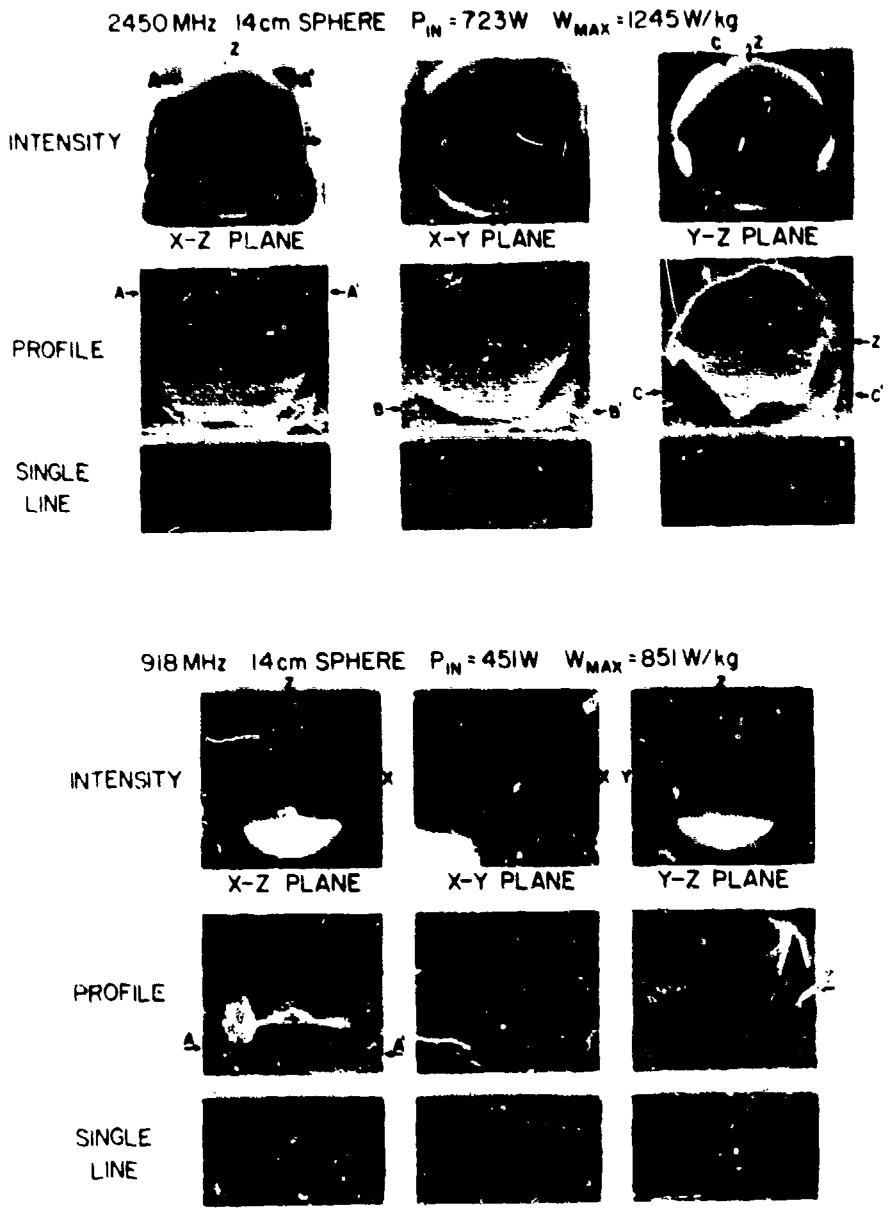


Fig. 21. Thermograms illustrating power absorption patterns for 14 cm diameter sphere exposed in 2450 MHz microwave ovens. Scale: horizontal - 1 div = 2 cm; vertical - 1 div = 3.33°C; vertical lines on single line scans indicate boundaries of object.

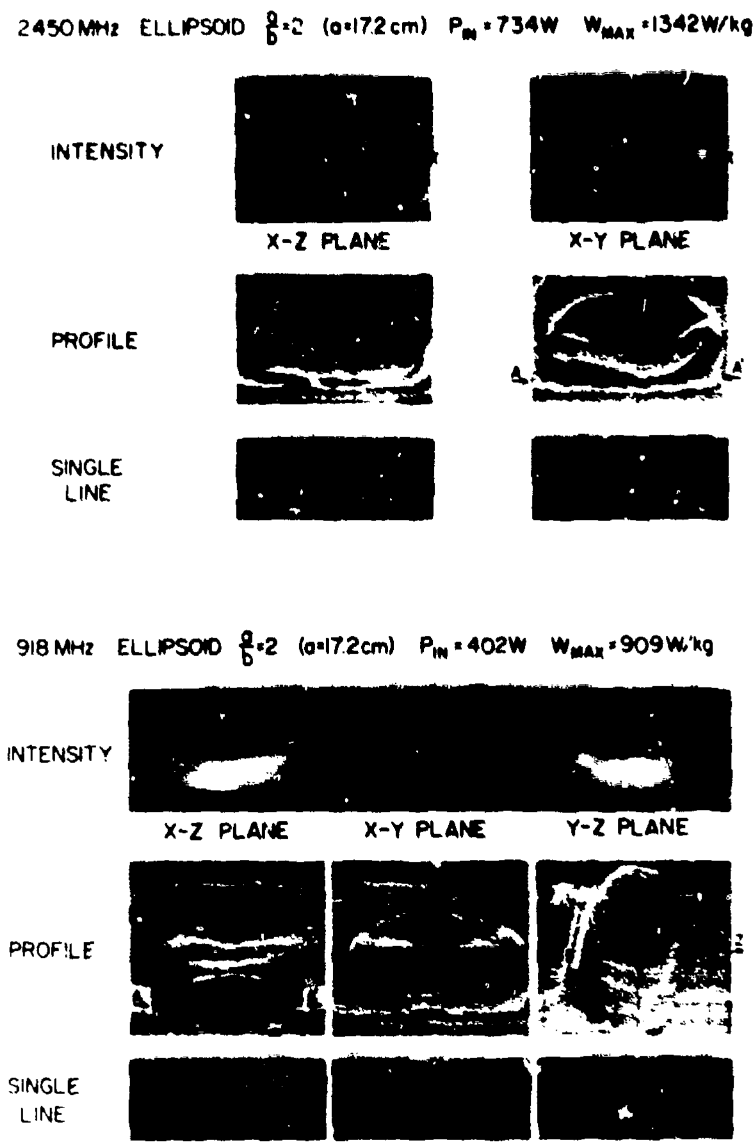


Fig. 22. Thermograms illustrating power absorption patterns for 17.2 cm 2:1 axial ratio ellipsoid with major axis oriented along x axis exposed in 2450 MHz and 918 MHz microwave ovens. Scale: horizontal - 1 div = 2 cm; vertical - 1 div = 3.33°C; vertical lines on single line scans indicate boundaries of object.

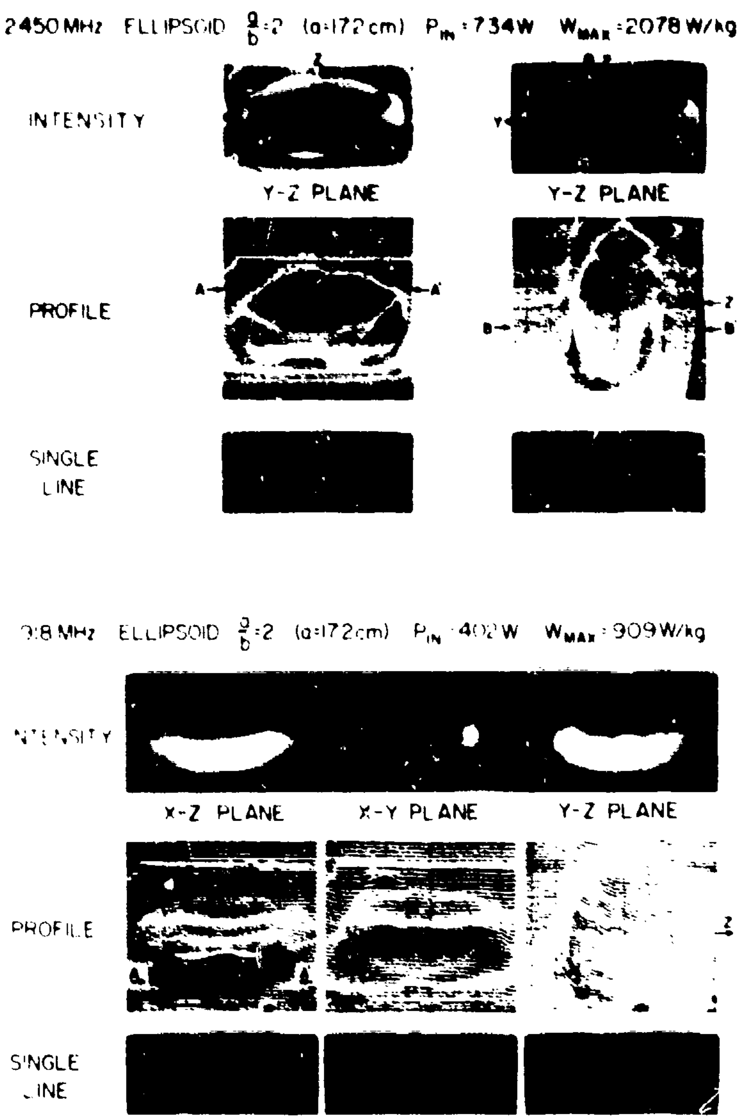


Fig. 23. Thermograms illustrating power absorption patterns for 17.2 cm 2:1 axial ratio ellipsoid wich major axis oriented along v axis exposed in 2450 MHz and 918 MHz microwave ovens. Scale: horizontal - 1 div = 2 cm; vertical - 1 div = 3.33°C; vertical lines on single line scans indicate boundaries of object.

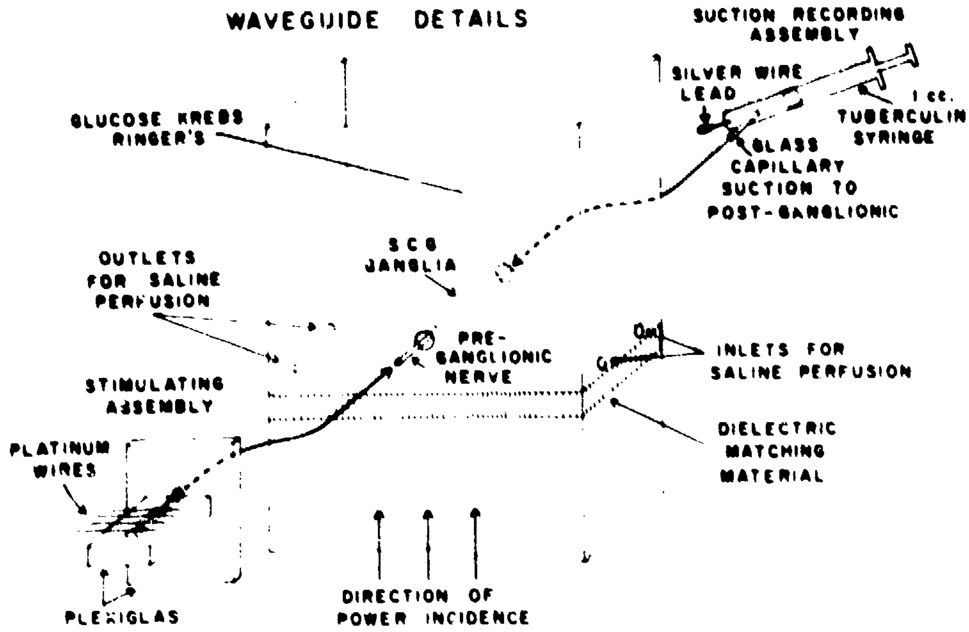


Fig. 24. Waveguide exposure facility for isolated superior cervical ganglion showing the stimulating and recording assemblies.

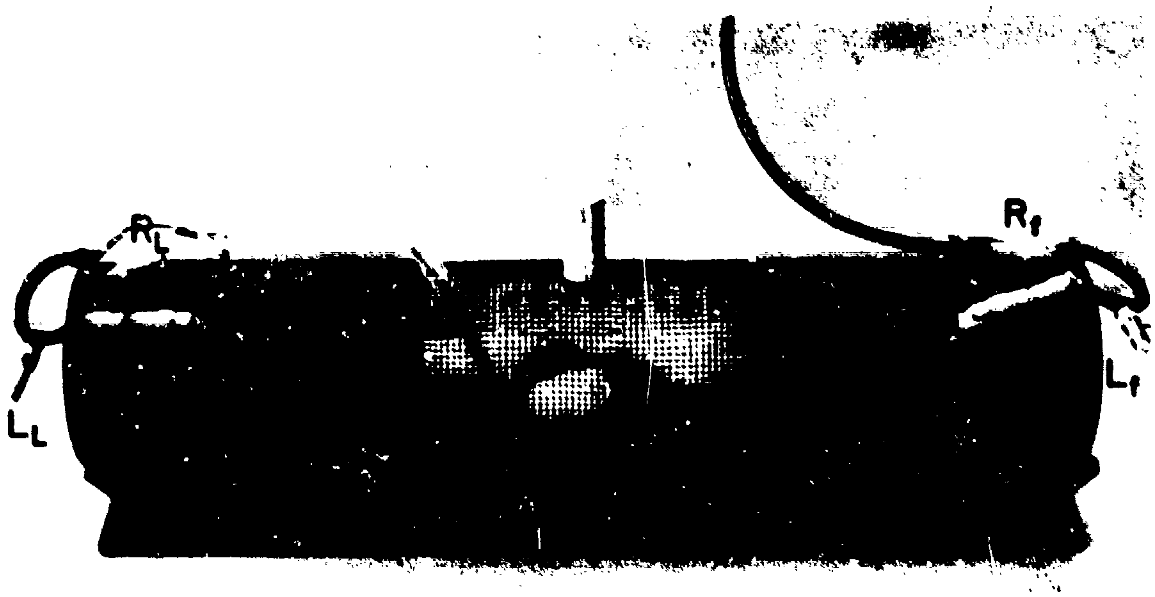


Fig. 25. Cell for chronic exposure of rat to circularly polarized guided EM waves.

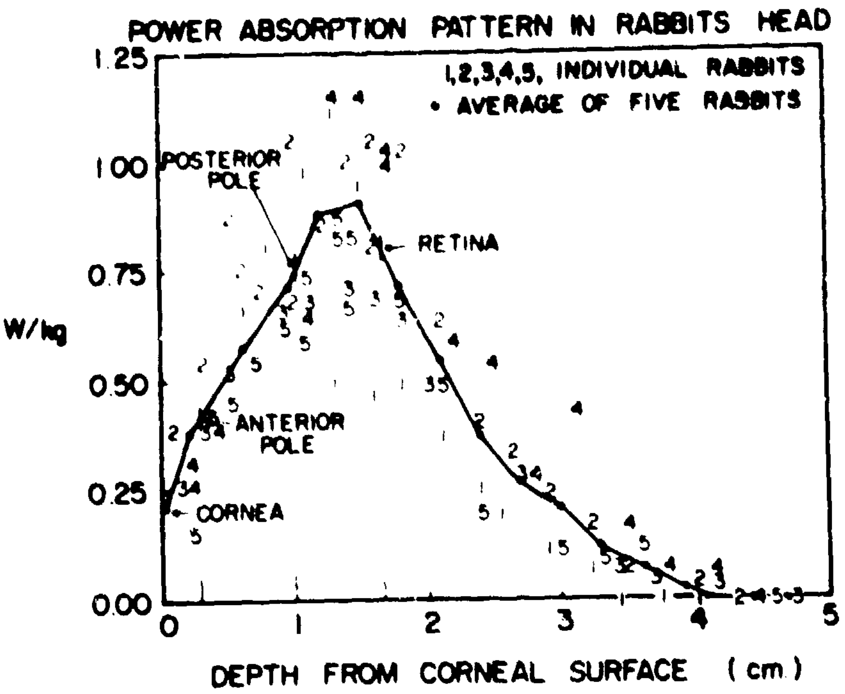


Fig. 26. Power absorption pattern in the eye and head of rabbit exposed to near zone 2450 MHz radiation per 1 mW/cm² incident power density.

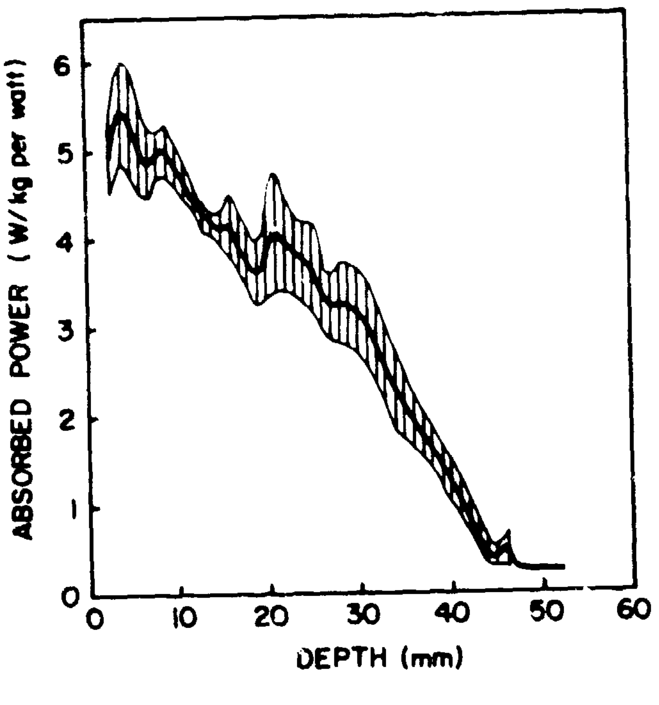


Fig. 27. Measured power absorption density in eye and head of rabbit exposed to resonant slot source.

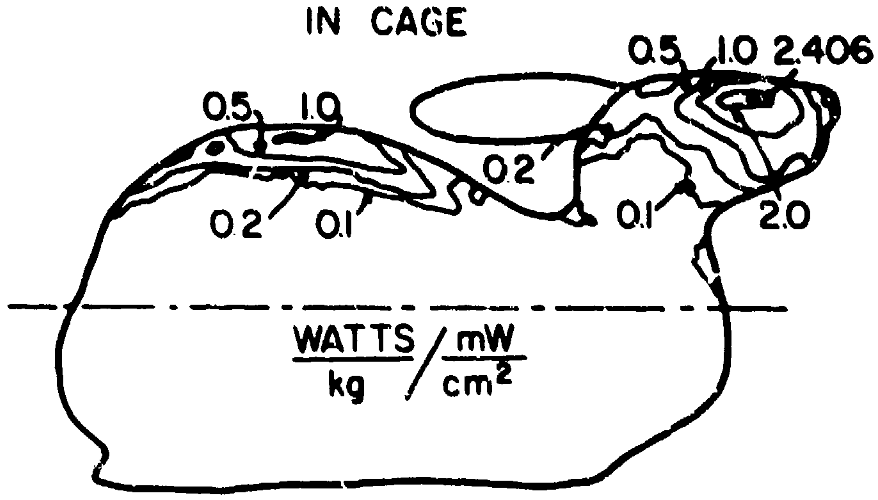


Fig. 28. Power absorption density pattern in rabbit exposed to 2450 MHz fields (normalized to measured incident power density at rabbit body axis).

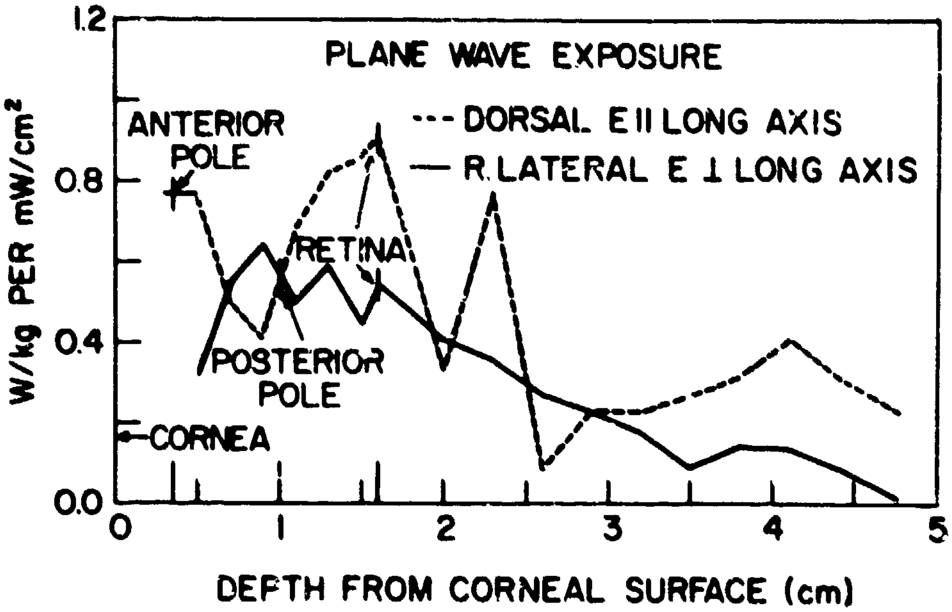


Fig. 29. Measured absorbed power density in eye and head of rabbit exposed to plane wave.

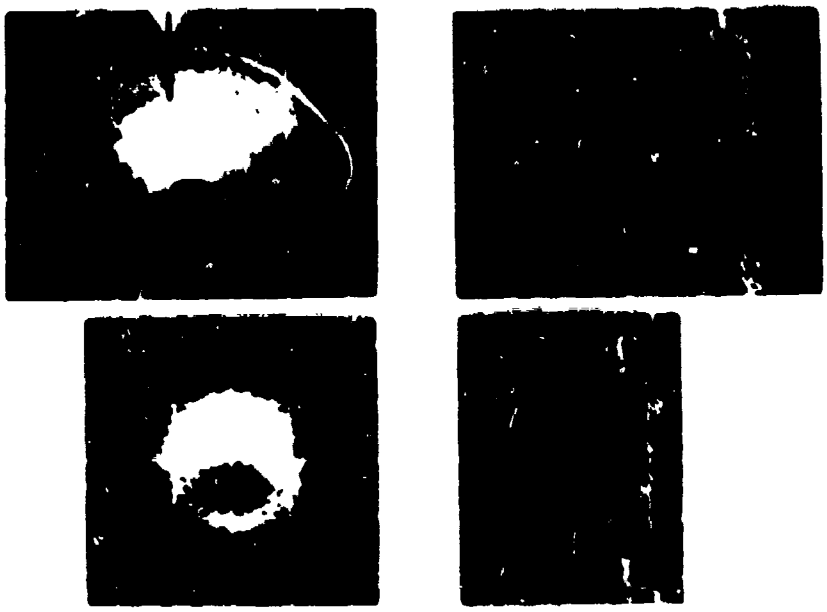


Fig. 30. Comparison between power absorption in cat head and 6 cm diameter phantom sphere (brain tissue) exposed to 918 MHz aperture source as measured with thermograph (peak absorption approximately 0.8 W/kg per mW/cm² incident power). (from Guy [2])

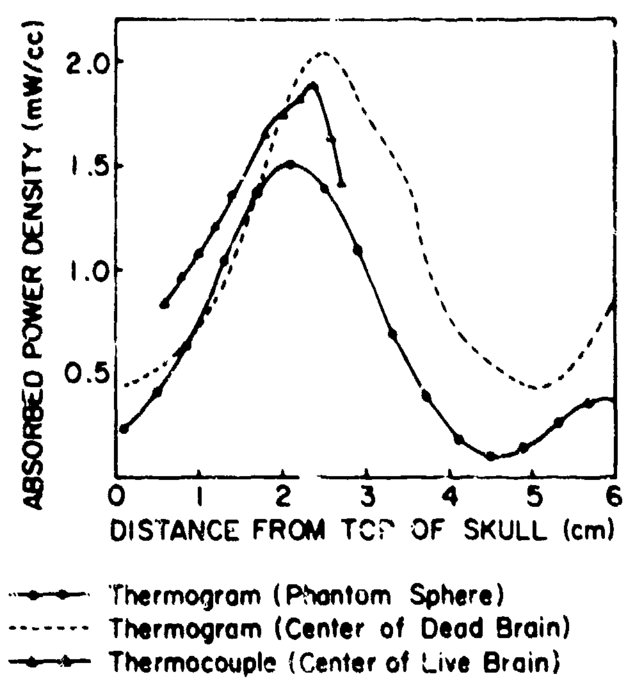


Fig. 31. Measured absorbed power patterns in cat brain due to microwave radiation from 918 MHz aperture source (spacing 8 cm with 1-W input power). (from Johnson and Guy [11])

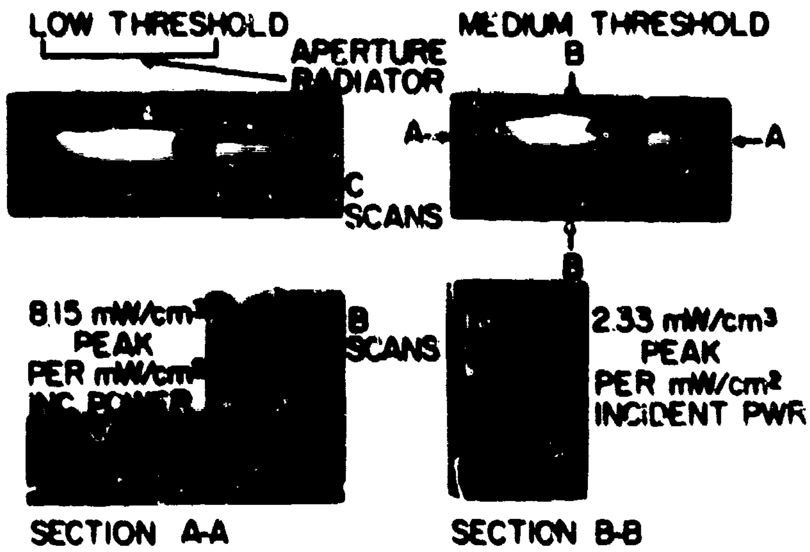


Fig. 32. Thermograms of phantom rat exposed to 918 MHz square aperture source. (from Guy [2])

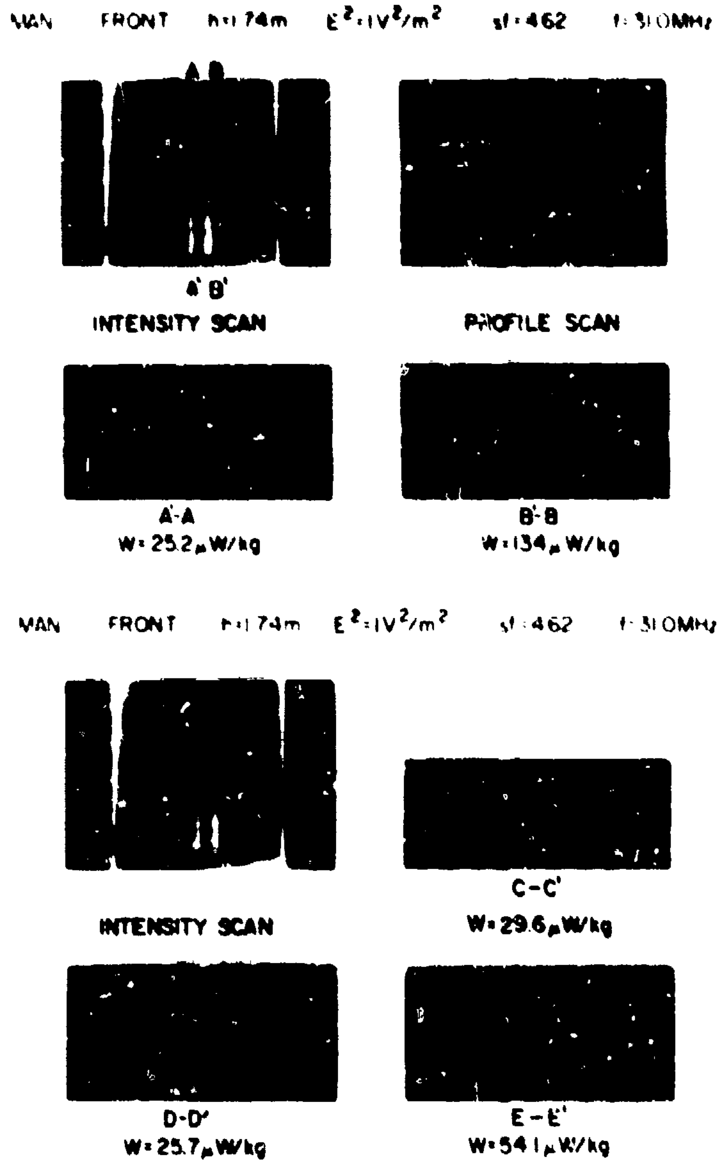


Fig. 33. Scale model thermograms and measured peak absorbed power densitites for 70 kg 1.74 m height frontal plane front model man exposed to 31.0 MHz electric field: Vert. div = 2°C; Hor. div = 4 cm.

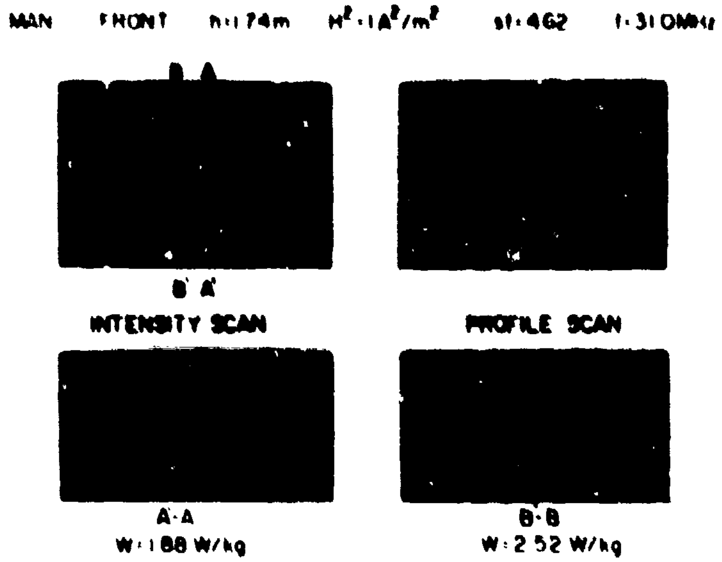


Fig. 34. Scale model thermograms and measured peak absorbed power densities for 70 kg 1.74 m height frontal plane front model man exposed to 31.0 MHz magnetic field: Vert. div = 2°C; Hor. div = [illegible] cm.

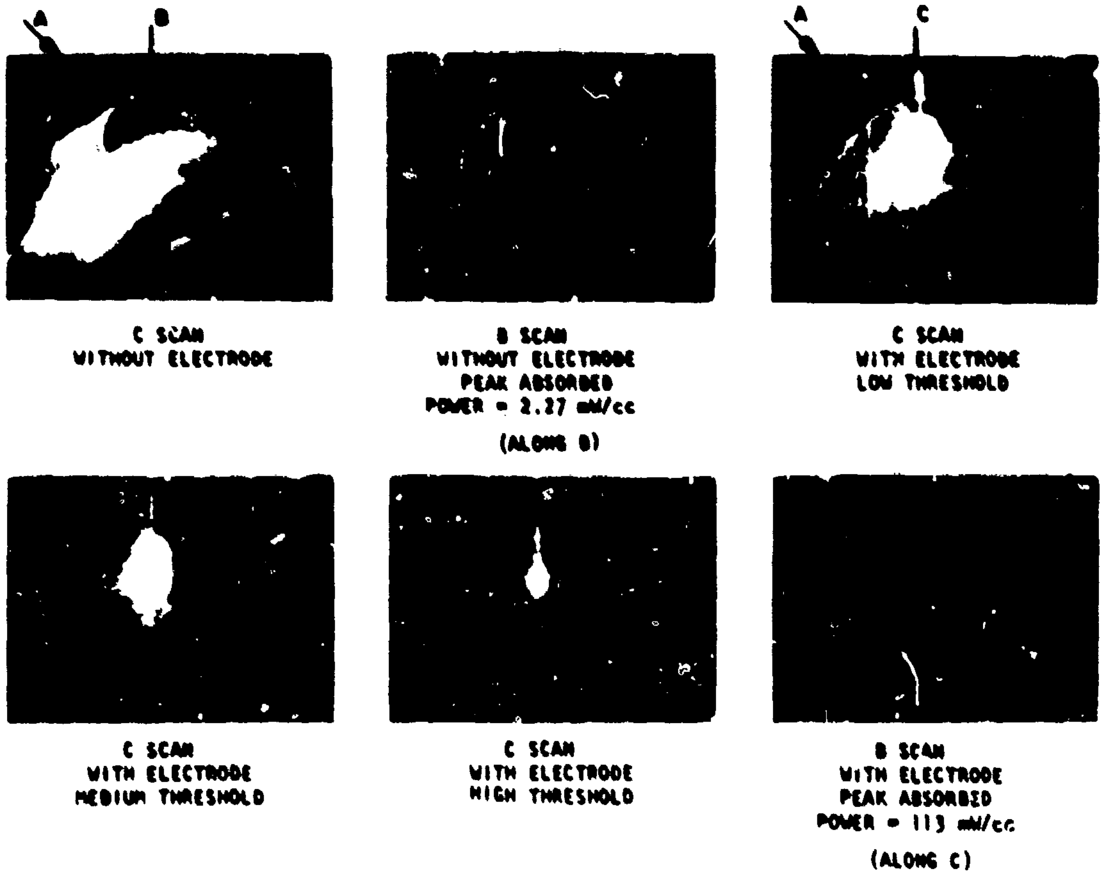


Fig. 35. Thermographic study of effect of coaxial electrode on microwave absorption pattern in the brain of a cat exposed to 918 MHz aperture source (incident power density = 2.5 mW/cm² scale, 1 division = 2 cm).

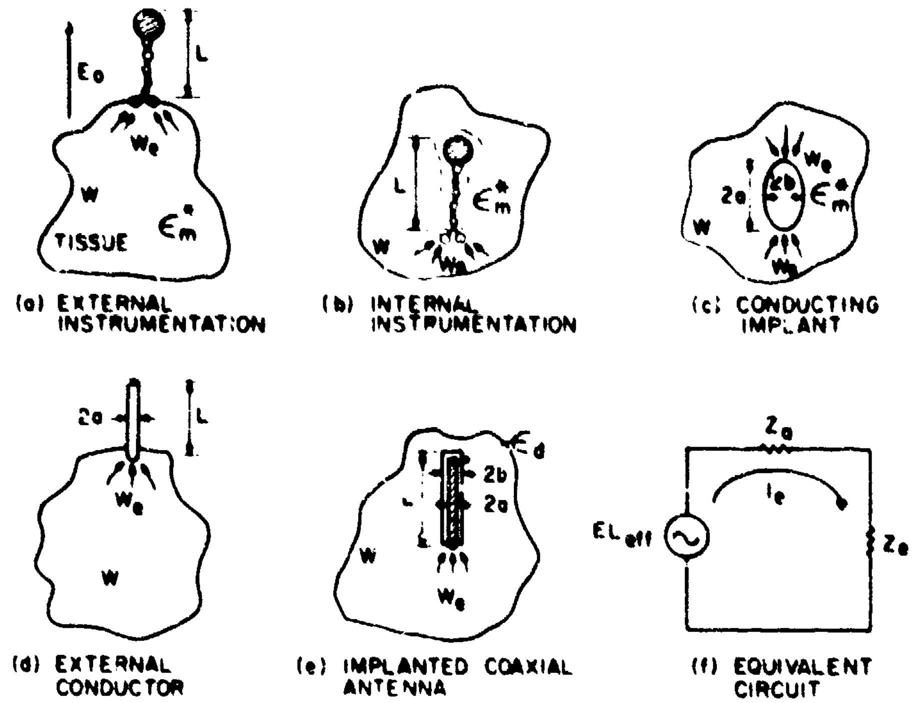


Fig. 36. Various cases of instrumentation and implants causing enhancement of fields in tissue bodies exposed to EM fields.

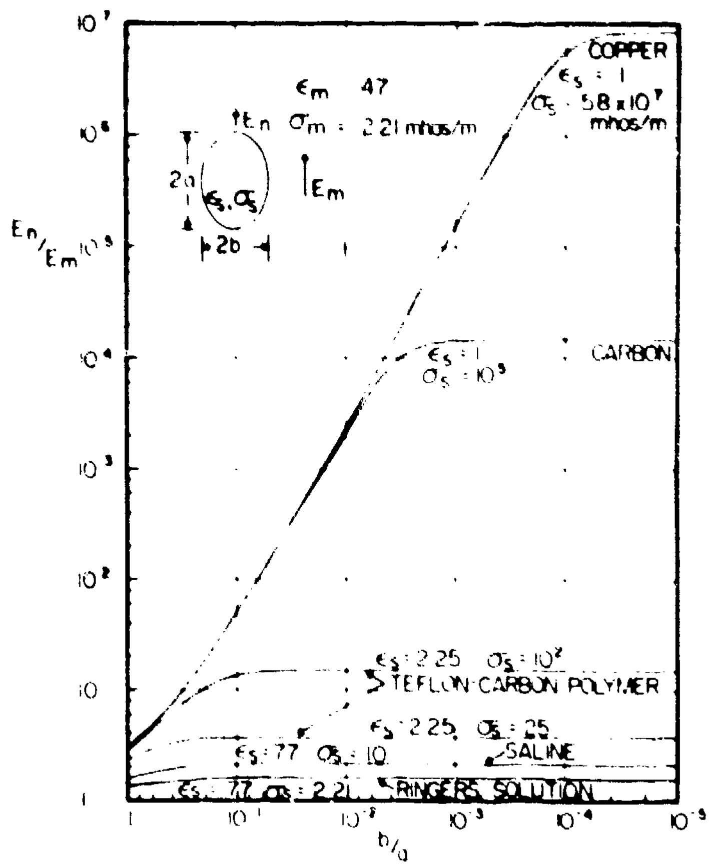


Fig. 37. Fields normal to end of imperfectly conducting dielectric prolate ellipsoid in muscle tissue. (Normalized to applied quasi-static field EM in muscle medium).

ELECTROMAGNETIC INTERFERENCE OF CARDIAC PACEMAKERS

by

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SUMMARY

The effect of electromagnetic radiation (EMR) on cardiac pacemakers is a unique bioeffects problem. The purpose of this lecture is to present the current state-of-technology concerning this effect. Current test procedures including methods to simulate pacemaker implant conditions and the use of fiber optics instrumentation techniques for cardiac simulation and pacemaker interference evaluation are presented. Test results and their clinical significance are discussed for different types of EMR emissions including microwave ovens, electrical appliances, gasoline engine ignition, radar, and intense electromagnetic pulse generators. Reported threshold values for pacemaker electromagnetic interference (EMI) range from 10 V/m for the more sensitive devices to greater than 300 V/m for the less susceptible devices. Such EMI threshold values are further modified by the frequency and pulse width of the incident EMR signal. Maximum interference coupling appears to occur at frequencies between 100 and 500 MHz and the EMI threshold is inversely proportional to pulse width over the range from one microsecond to several milliseconds. The ultimate biological effect is dependent on the characteristics of the EMR source, the proximity of the pacemaker user to the source, the attenuation afforded by body shielding and orientation, and the state-of-health of the pacemaker user. The test results presented provide considerable evidence that many manufacturers have recognized EMI as a potential bioeffects problem and have taken the necessary corrective actions to build devices with good electromagnetic compatibility (EMC). Continued awareness of potential interference conditions by manufacturers, physicians, and pacemaker users will eventually resolve this problem and serve as the basis for good EMC design for future medical prosthetic devices.

INTRODUCTION

During the past decade the electronic cardiac pacemaker has been developed into a sophisticated prosthetic device. It is applied in medical facilities throughout the world to correct malfunctions (atrio-ventricular heart block) of the body's electrical conduction system to restore the rhythmic pumping action of the heart.

At least fifty different companies manufacture pacemakers, and some manufacturers have ten or more different models (electronic design and function). Figure 1 illustrates 16 different pacemakers made by ten different companies. In general, pacemakers may be classed as fixed rate (asynchronous) and demand (synchronous or R-wave inhibited). Fixed rate pacemakers provide a fixed, preset rate of electrical stimuli to the ventricles which is independent of the electrical and/or mechanical activity of the heart. Demand pacemakers sense the depolarizations of the heart muscle activity and produce their own depolarization signals (electrical stimulus) only if the normal heart depolarizations are not present. The atrial synchronous pacemakers sense the depolarization of the atria, delay the signal to simulate natural conduction time, and then provide the electrical stimulus to the ventricles. The R-wave inhibited demand pacemaker senses depolarization of the ventricles if it occurs naturally and inhibits its output; i.e., the pacemaker functions only when the AV heart block occurs (1).

Most of the pacemakers implanted today are of the R-wave inhibited type. They contain an electronic timing circuit which is reset by normal depolarization or the pacemaker stimulus. Their sensing circuit is programmed to respond to electrical signals normally generated by the heart. Thus, energy pulses induced externally via the pacemaker leads or circuitry can erroneously cause the pacemaker to inhibit its needed output.

Essentially, all demand pacemakers have interference rejection circuitry which, upon sensing external electromagnetic (EM) interference having basic pulse repetition rates (PRR) greater than 50-60 Hz, will revert to a fixed rate mode of operation. This is judged a nonhazardous form of interference. However, external EM signals having a PRR in the range of 1 to 10 Hz and energy pulses greater than the pacemaker's interference threshold value will cause the pacemaker to inhibit, and this is a potentially hazardous situation for the pacemaker user (2, 3, 4).

Case histories of pacemaker interference reported in the open literature substantiate the potential problem (5-11), although many cases of pacemaker EMI probably go unreported due to the nature of the interference phenomena. For instance, upon sensing external EM radiation, many pacemakers revert to a fixed rate sufficiently close to their demand rate that the user would not normally detect the change.

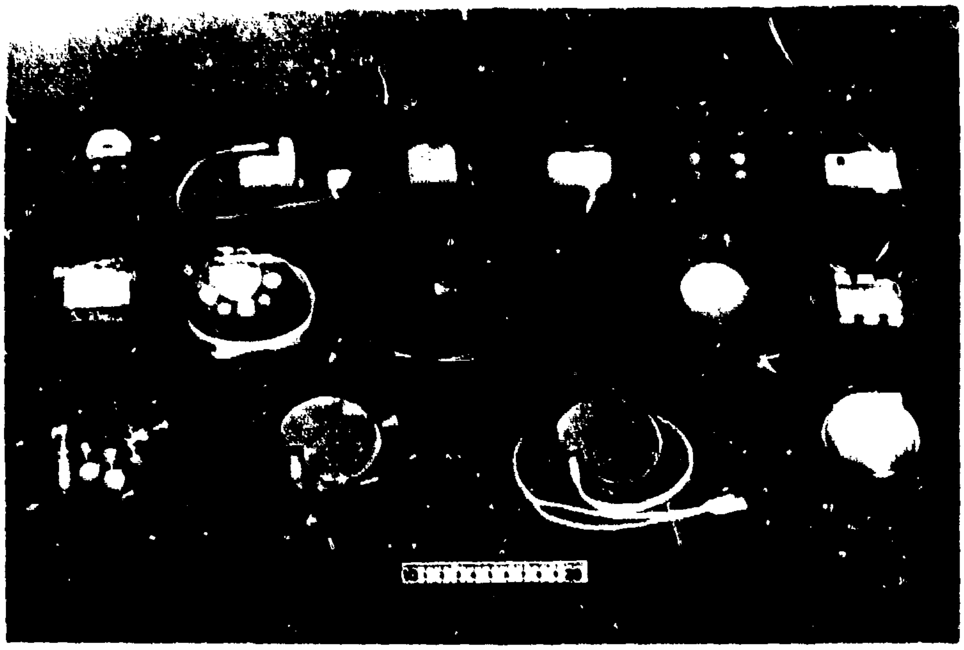

Figure 1. Cardiac Pacemakers

Top Row: Stimtech 3821; General Electric A2075A; Medcor 3-70A; Starr Edwards 8116 and 8114; Pacesetter BD-101

Middle Row: American Optical 281003 and 281143; Biotronik IDP-44; Cordis 162C and 164A; Vitatron MIP-40-RT

Bottom Row: Medtronic 5842, 5942, 5944, and 9000

High power radiofrequency radiation emitters such as air route surveillance radar can cause many pacemakers to miss single beats as the radar beam scans past, an effect most likely unnoticed (2). Even more serious interference may not be identified because, most often, interaction times are short, i.e., either the source of EMI is moved or turned off or the user moves from the particular area of the effect. Additionally, little postmortem followup is made of pacemaker users to identify any possible causal relationship to EMI.

Notwithstanding the preponderance of EMI data now available and general acknowledgement of the potential hazard to individual users, controversy will continue as to the clinical significance of this effect of EMR on the pacemaker populace (12, 13).

Test procedures, instrumentation techniques and EMI test results are presented as a technological overview of the state-of-knowledge at this time concerning the interaction of EM fields and cardiac pacemakers.

TEST PROCEDURES

Implant Simulation

Realistic assessment of the effects of EMR on cardiac pacemakers must be made under actual implant conditions or accurate simulation of implantation. Initial EMI studies by the USAF School of Aerospace Medicine were conducted by implanting pacemakers in 18-20 kg dogs and effecting a complete atrioventricular heart block (14). This procedure is costly and has obvious disadvantages in having to handle the animals under a variety of test conditions in the laboratory and at remote test sites. Thus, alternate techniques have been developed to simulate the pacemaker implant.

The Association for the Advancement of Medical Instrumentation (AAMI) working under a contract with the U.S. Food and Drug Administration (FDA) has developed a draft protocol for testing cardiac pacemaker EMI characteristics. They recommend using a 80 cm x 40 cm x 20 cm container made of 5 cm thick plastic foam (density of 0.035 g/cm^3). The container is filled with 0.03 molar saline solution and the pacemaker and leads are located to place 1 cm of solution between the pacemaker and the wall of the container. A similar arrangement used in the USAFSAM tests provided good correlation between this method of simulated implant and the implanted dogs (4, 14). With the many variables (body size, location,

depth of implant) in actual human implants, it is felt this procedure for implant simulation is sufficient for EMI testing.

Instrumentation

Many different types of instrumentation techniques have been used in cardiac pacemaker EMI testing (2, 4, 7, 14, 15). The principal requirement is that the instrumentation system be immune to the EM fields encountered in the tests and that it present to the pacemaker a load and signal simulating those encountered in an actual implant situation so that the results obtained apply to a human implant. The system should also provide real time recording of the incident EMR signal and the pacemaker response.

Several models of pacemakers have interference rates identical to their demand rates, so it is often difficult to determine susceptibility thresholds for pacemakers in EMR fields having pulse repetition rates sufficient to cause the pacemaker to revert to its fixed rate. The minimum PRR values range from 10-60 Hz depending on the specific pacemaker. Thus, a method to simulate normal heart activity at the pacemaker leads is required so that an R-wave inhibited pacemaker would be inhibited by this simulated activity and would not produce a pulse until it detected interference and reverted to its interference mode. An additional requirement is imposed for a synchronous pacemaker to track the simulated activity up to its interference threshold. A system of this type has been developed and incorporates a light-emitting diode (LED) fiber optics monitoring system (16).

The system was developed to present a resistive load near the upper limit encountered with implanted pacemakers. Such a circuit will limit the possible range of load resistance from 350-1000 ohms as the resistance across the jack varies from 0 to infinity (see figure 2). Thus, the firing of the LED will not radically change the load when the pacemaker pulses as would occur if the LED were connected in either series or parallel with the load. If the LED were connected in series with the load resistance, the load would be over 100 kilohms until the pacemaker pulsed; if the LED were connected in parallel, the load would drop to under 100 ohms when the pacemaker pulsed. This design also enables a magnetic earphone to be plugged into the jack to be used as an audio monitor to ensure that the pacemaker is properly connected to the load. The 1000-ohm resistor in parallel with the pacemaker (Fig. 2) is the load the pacemaker sees except when emitting a pulse, in which case the LED has a fairly low impedance (since it conducts during the pulse). When the LED fires, the load on the pacemaker is approximately 500 ohms, depending on the output voltage of the pacemaker.

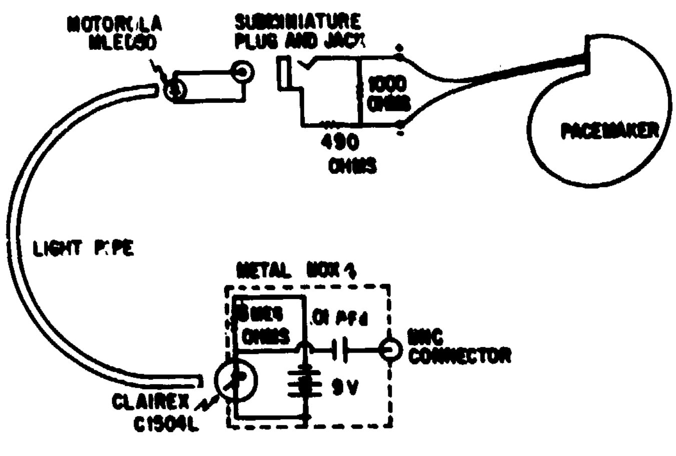

Figure 2. LED pacemaker monitor.

The LED is mounted in a subminiature audio plug. The light pipes are sheathed and contain approximately 36 plastic fibers. The end of the light pipe is held in contact with the LED by a friction fit between heat-shrink tubing over the plug and over the jacket of the light pipe. This enables the light pipe to be removed and exchanged for a longer or shorter length. The length of light pipe which can be used effectively is limited because of signal loss; however, lengths of about 3 and 8 meters have been used successfully.

With a device added to simulate cardiac output (16), the pacemaker testing system is a satisfactory simulation of the environment experienced by an implanted pacemaker. Figure 3 is a recording of two pacemakers' responses to the simulator: an R-wave inhibited pacemaker in both demand and fixed rate, and a P-wave synchronous pacemaker in both synchronous and fixed rate modes. These recordings illustrate the advantage of such a system to determine if the pacemaker is in an EMI mode.

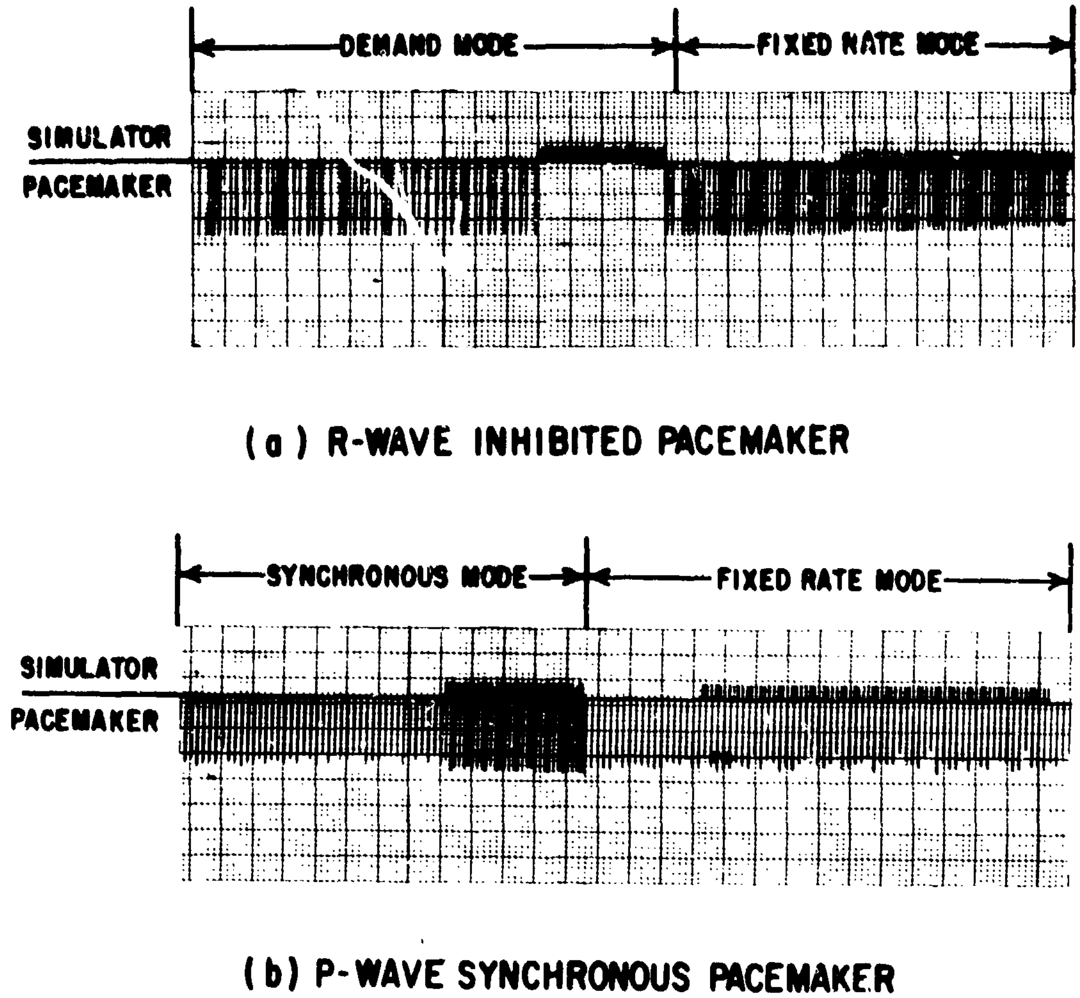

Figure 3. Pacemaker Responses to Cardiac Simulator

RESULTS

Microwave Ovens

Although most microwave ovens operate at 2450 MHz with 60 or 120 Hz modulation, the mechanical mode stirrer produces a second modulation of about 0.5 to 10 Hz (17). Many of the pacemakers in common use several years ago exhibited serious disruption by this type of EMR emission (6, 17, 18, 19). The pacemaker interference threshold was less than one microwatt/cm^2 resulting in the more sensitive devices being adversely affected at distances of several meters from the oven. The potential hazard of this type of pacemaker interference has been essentially eliminated with recent improvements in pacemaker circuitry and application of EMR shielding and filtering techniques, coupled with more stringent control of microwave oven leakage.

Electrical Appliances and Engine Ignition

The EMR emission from a large number of electrical appliances (drills, saws, food mixers, hair dryers, razors, vacuum cleaners, etc.) and the ignition of gasoline engines (powerboat motors, automobiles, lawn mowers, etc.) can cause pacemakers to exhibit reversion to fixed rates, inhibition (cutoff), and tachycardia (3, 7). However, in almost all such cases the pacemaker must be within about 0.5 meter of the source to be adversely affected. Thus, as in the case of microwave ovens, such sources of EMI are not considered a serious threat to most currently marketed pacemakers.

High Power EMR Emitters

Many different types of high power EMR emitters ranging from television transmitters to radar can

produce pacemaker interference (2, 5, 8, 9). Typical of such emitters are the Air Route Surveillance Radars in operation throughout the world to monitor the flight paths of aircraft. These systems propagate ~1-5 megawatts peak power at frequencies between 1-3 GHz with pulse repetition rates (PRR) of 200-400 pps, and pulse widths (PW) of 2-10 microseconds. They rotate at 5-6 rpm and operate 24 hours per day, 7 days per week. Though they are usually located on 15-25 meter towers, they produce sufficiently intense EMR signals at ground level to disrupt some pacemakers at distances of 300 meters or more from their antenna (2). Figure 4 is a typical plot of the real time EMR field intensity in volts per meter at ground level ~650 meters from such emitters.

Chart Speed - 20 mm/sec

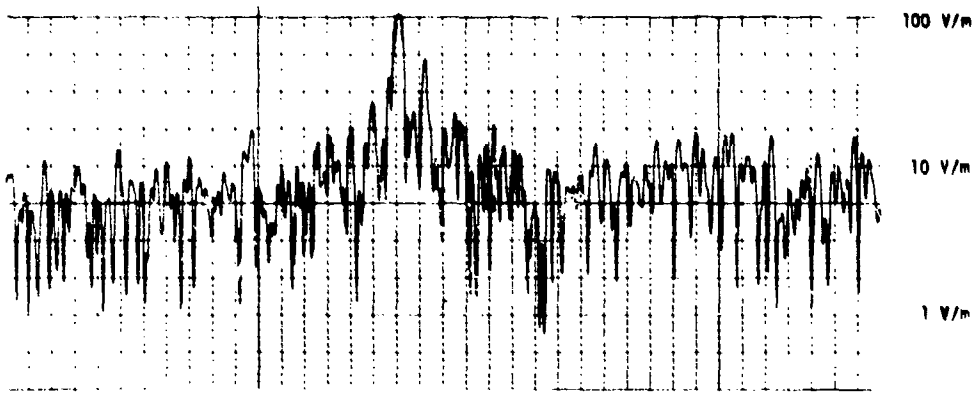

Figure 4. Typical Plot of Real Time EMR Field Intensity ~650 Meters from Air Route Surveillance Radar.

Pacemakers may often miss single beats in the vicinity of such radar as the main beam passes overhead resulting in the loss of 5-6 beats per minute (bpm). Figure 5 is a typical recording of this effect. At closer approaches to such emitters, the pacemaker EMI threshold may be exceeded by other peaks of the lobe structure (shown in figure 4) resulting in a further reduction of pacemaker rate. Figure 6 is a typical recording of this effect. Additionally, the lobe structure can appear as a 1-10 Hz EMR signal which the pacemaker can sense as heart activity and the pacemaker will inhibit (cut off) altogether.

In general, the EMR electric field (E-field) intensity at ground level does not exceed 100 volts per meter for significant periods of time. Therefore, the pacemakers having EMI thresholds greater than 100 V/m should not be seriously affected.

Electromagnetic Pulse

Electromagnetic pulse (EMP) facilities are unique sources of EMR emission which produce intense pulses (up to 100,000 volts per meter) in ~0.5 microsecond with ~90% of the frequency components below 10 MHz. Tests conducted by USAFSAM included the exposure of eight dogs, implanted with different types of pacemakers (14), to single pulses at 5, 25, and 50 kV/m. On the basis of electrocardiograph recordings made before and after exposure, it was determined the pacemakers were not seriously disrupted.

In studies using EMP sources in a repetitively pulsed mode, an EMI level of 500 V/m was established as the threshold for serious effect. These tests were conducted under simulated implant conditions for peak E-field levels from 300 V/m to 6000 V/m with PRR values from 2 to 100 pps.

Laboratory Tests (450 and 3100 MHz)

Recent cardiac pacemaker EMI tests were conducted under controlled laboratory conditions using square wave modulated 450 and 3100 MHz EMR fields (4). The purpose of these tests was to evaluate the overall improvement in EMI thresholds when compared with tests conducted 2-3 years earlier. Seventy-two pacemakers representing ten manufacturers and twenty-three different designs were tested. The 450 MHz fields were circularly polarized with E-field levels up to 292 V/m. The ranges of PW and PRR used were 1 microsecond (μsec) to 1 msec and 2-50 pps, respectively. The 3100 MHz fields were vertically polarized with levels up to 320 V/m (rms) for a PW range of 10-120 μsec at 7-400 pps. The pacemakers were positioned in the "far-field" region of the anechoic chamber in the EMR beam center and tested in a simulated implant configuration similar to that described above. The pacemaker response was recorded via a fiber optics telemetry system as described above and by Steiner in a recent School of Aerospace Medicine Technical Report (16).

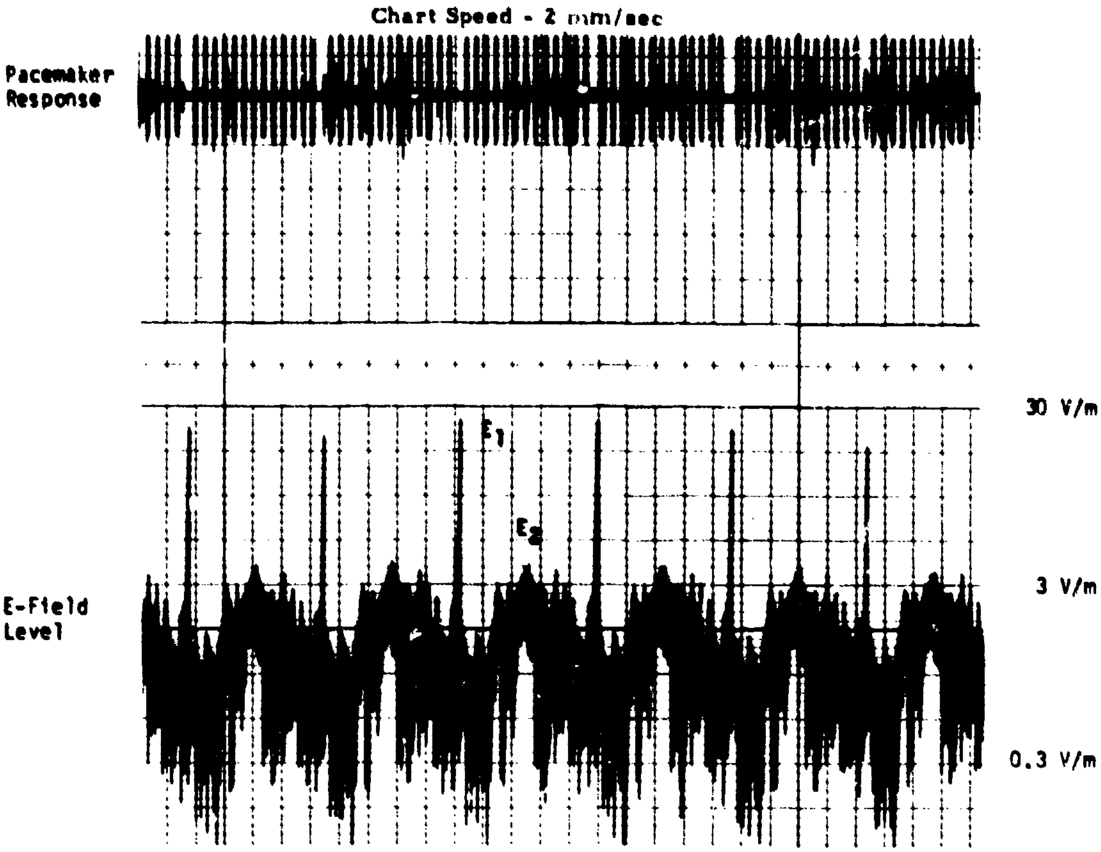

Figure 5. Example of interference which causes pacemaker to skip single beats as main beam of radar sweeps past on each 360° scan. Pacemaker rate: 64 bpm.

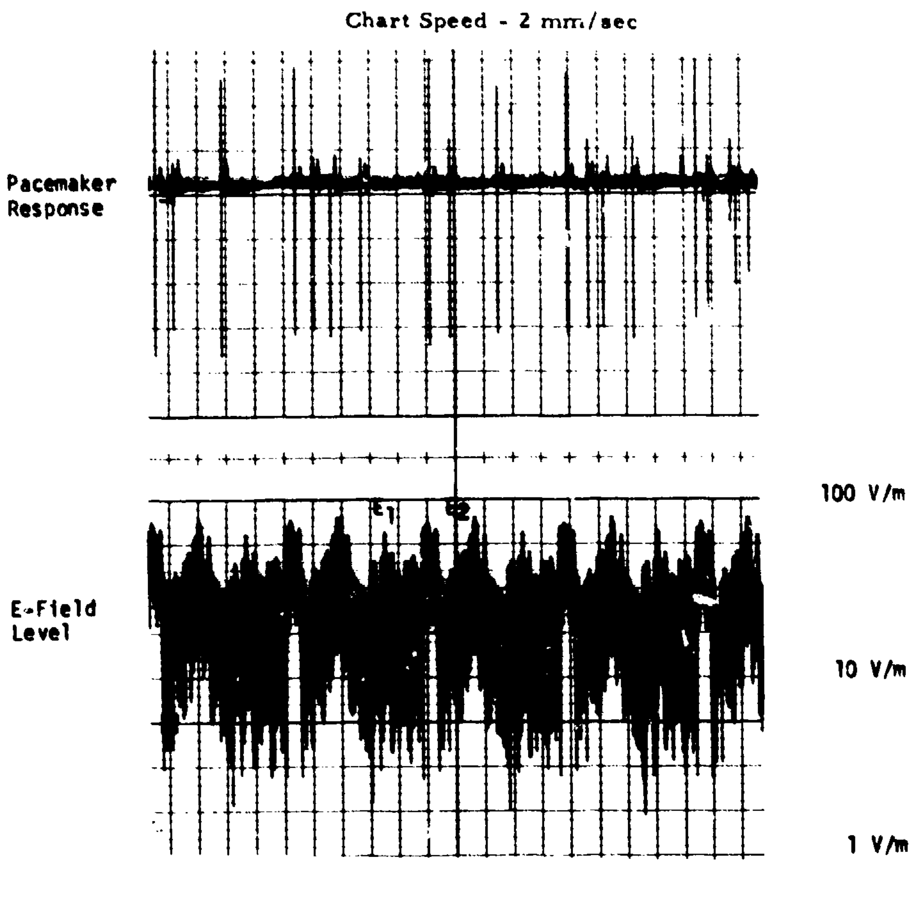

Figure 6. Example of serious pacemaker interference near radar. Pacemaker rate: 16 bpm.

Table I summarizes the EMI adverse effect threshold values for the 23 models (types) tested under simulated implant conditions at 450 MHz. An adverse effect is defined as a pacemaker rate which falls below 50 beats per minute (bpm) or exceeds 125 bpm as a direct result of EMI. In most instances the value at which the most sensitive of so-called identical pacemakers cut off completely was selected as the adverse effect threshold. In cases where the threshold is based on an increased rate, it was generally observed that the pacemaker rate continued to increase with increasing EMR field level. Where no adverse effect was observed at the maximum field level available, it is noted by >300 V/m. Blank spaces indicate the other data points are adequate to describe the effect.

TABLE I

SUMMARY OF ADVERSE EFFECT THRESHOLDS FOR
CARDIAC PACEMAKER ELECTROMAGNETIC INTERFERENCE
(SIMULATED - IMPLANT CONDITIONS)

Pacemaker Manufacturer and Model Number	Frequency 450 MHz, Pulse Width 1 msec — Pulse Repetition Rate in pps: 2	10	20	40
	V/m(bpm)	V/m(bpm)	V/m(bpm)	V/m(bpm)
1. American Optical 281003	13(0)		15(0)	243(0)
2. American Optical 281013	26(0)		26(0)	
3. American Optical 281143	>300			>300
4. Biotronik IDP44	141(0)	>300	>300	>300
5. Cordis Atricor 133C7	>300	>300		141(172)
6. Cordis Omni-Atricor 164A	>300	>300		>300
7. Cordis Stanicor 143E7	15(0)	15(0)	243(0)	>300
8. Cordis Omni Stanicor 162C	8(0)	9(0)		>300
9. General Electric A2072D	29(0)	207(125)		
10. General Electric A2075A	23(0)	141(125)		
11. Medcor 3-70A	29(0)	141(0)	141(0)	141(0)
12. Medtronic 5842	15(0)		15(0)	15(0)
13. Medtronic 5942	12(0)		12(0)	12(0)
14. Medtronic 5943	23(0)		19(0)	>300
15. Medtronic 5944	26(0)	26(0)	>300	>300
16. Medtronic 5950	>300			>300
17. Medtronic 5951	>300			>300
18. Medtronic 9000	10(0)	10(0)	10(0)	>300
19. Pacesetter BD-101	>300			>300
20. Starr Edwards 8114	23(0)		>300	
21. Starr Edwards 8116	>300	>300		>300
22. Stimtech 3821	107(0)	114(0)	>300	
23. Vitatron MIP-40-RT	93(0)	107(0)	243(0)	243(0)

NOTE: The adverse effect threshold is assigned when the pacemaker rate falls below 50 beats per minute (bpm) or exceeds 125 bpm as a direct result of EMI.

The test data summarized in Table I serve to illustrate the wide range (8 V/m to >300 V/m) of EMI susceptibility thresholds among the 23 pacemaker models tested. Comparing the relatively new A.O. pacemaker (item No. 3) with the older A.O. models (Nos. 1 and 2) shows a dramatic improvement in EMI characteristics. The same is true for the new Starr-Edwards model 8116 compared to their model 8114. It is also noteworthy that the relatively new Pacesetter pacemaker was not affected by the maximum EMR levels available in these tests indicating that EMI characteristics were considered during the design stages. Again as in tests conducted two years ago, the Biotronik pacemakers (obtained just prior to these tests) maintained good EMI characteristics. Although the improvements in EMI characteristics were much greater for some models, it appears that all of the manufacturers are including EMI as a design consideration and in essentially every case the newer models show improvement in this respect.

The data in Table I also illustrate a relatively wide range of PRR values for reversion to fixed rate, some pacemakers reverting upon sensing EMI at pulsed rates less than 10 pps while others have not reverted at 40 pps. The newer pacemakers demonstrate good improvement in this area. For example, the new Medtronic pacemakers now revert to fixed rate at lower PRR values.

The tests conducted at 3100 MHz using 120 microsecond pulses and maximum EMR fields of 320 V/m with the pacemakers exposed in a simulated-implant configuration caused very few adverse EMI effects. All adverse effect thresholds were greater than 200 V/m. The PW studies described below indicate the 3100 MHz EMI thresholds would be much lower if the PW were increased.

At 450 MHz, EMI thresholds were measured for PWs between 1 μsec and 1 msec at 2 pps and 50 pps (Fig. 7). Each curve generally represents data from more than one pacemaker. There was no significant difference between the 2 pps and 50 pps data. The constant pulse energy density curve shows the relation between PW and the product of power density during the pulse and PW (energy density). These data demonstrate that the EMI response threshold is inversely proportional to PW.

For 3100 MHz, a PW range of 10-120 μsec for 7 pps and 400 pps was investigated (Fig. 8). The data were normalized to the 120 μsec points. The G.E. model A2072D was the only pacemaker which demonstrated a significant difference in relationship between threshold and PW for different PRRs. The 3100 MHz data also demonstrated that the E-field threshold is inversely proportional to PW.

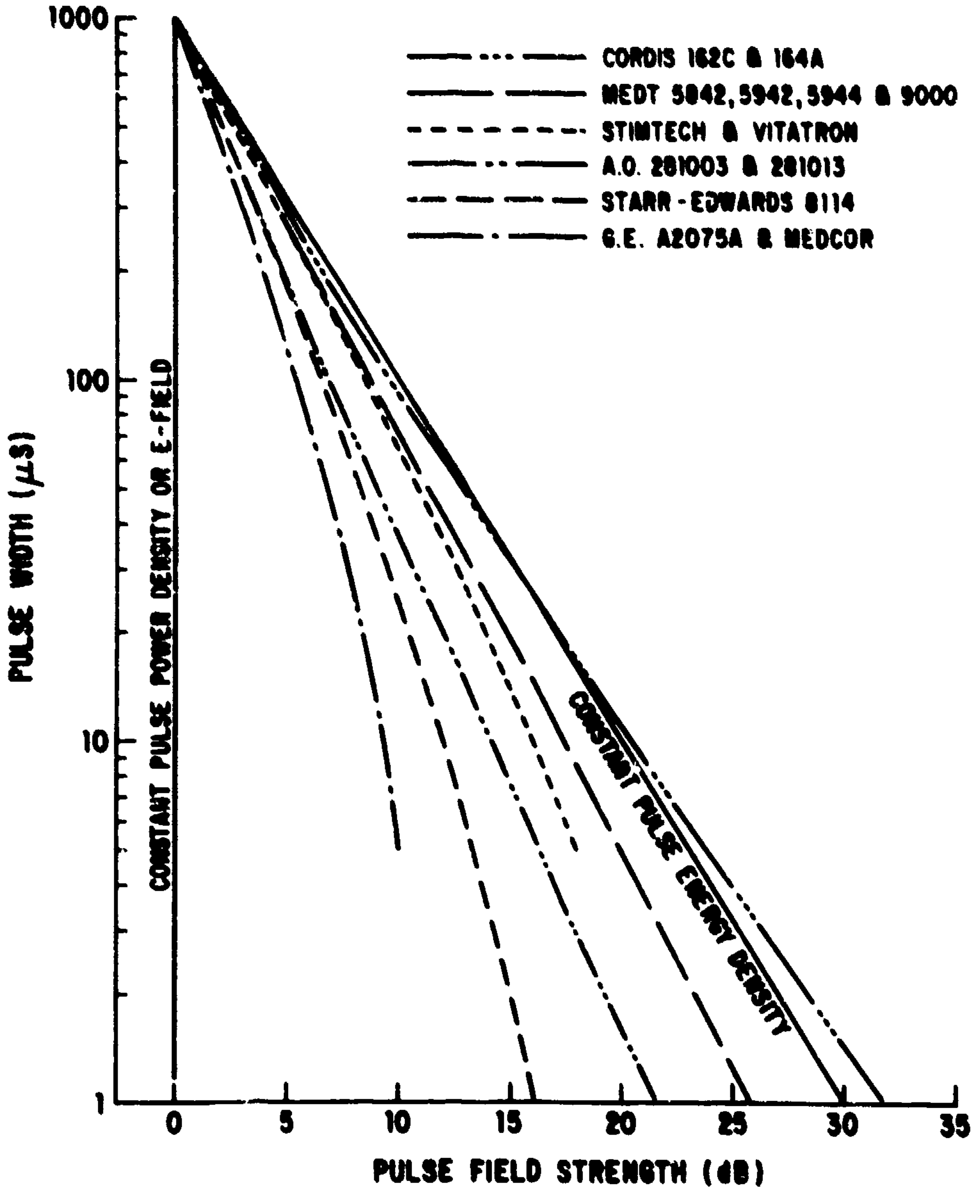

Figure 7. Relative pacemaker EMI thresholds vs. PW (450 MHz)

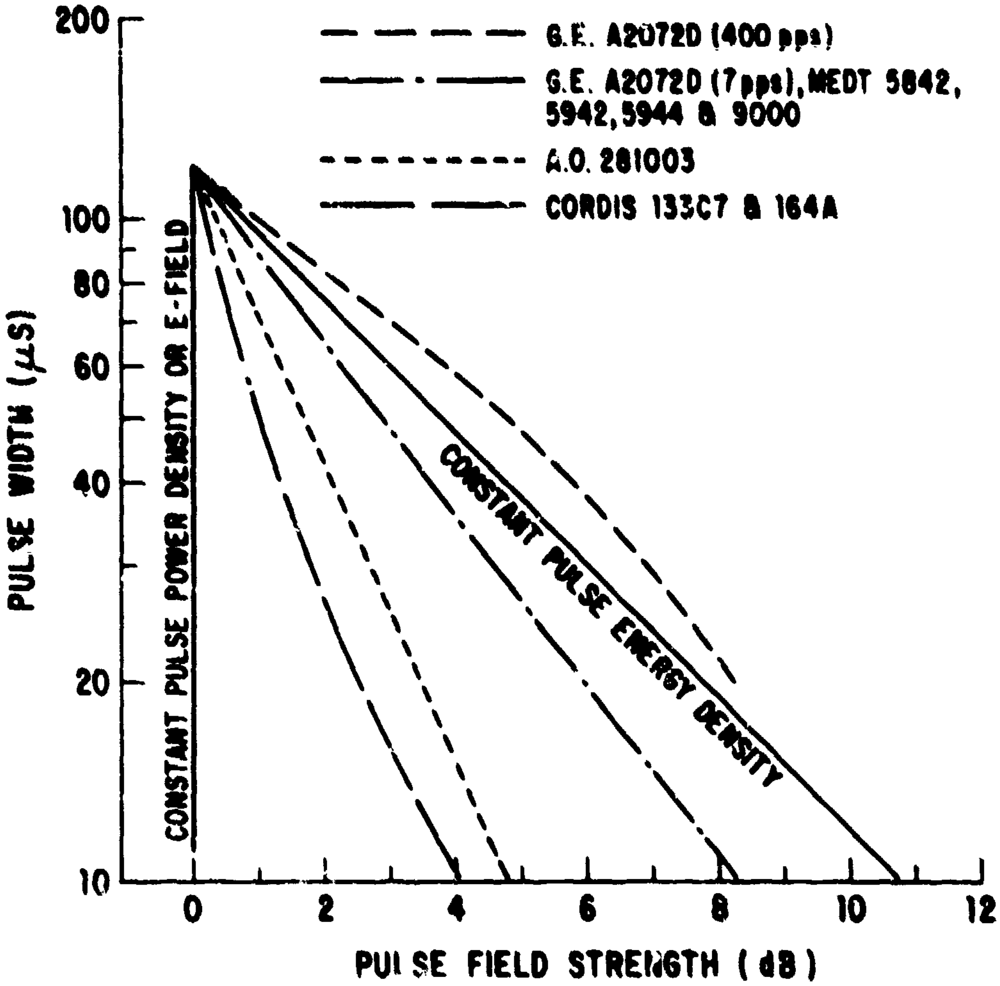

Figure 8. Relative pacemaker EMI thresholds vs. PW (3100 MHz)

DISCUSSION

Electromagnetic radiation having a field intensity above a certain threshold value (dependent on the specific pacemaker) can disrupt the normal pacemaker function and create a potential hazard for the user. The extent and significance of such EMI is dependent on many factors including:

(1) The frequency of the incident EMR signal. Available test data indicate maximum interference coupling at frequencies between 100 and 500 MHz.

(2) The pulse width (PW) or energy density of the EMR signal. The interference threshold in volts/meter is inversely proportional to PW.

(3) The pulse repetition rate (PRR). If the EMR field intensity is changing in such a manner to mimic a PRR of about 1 to 10 pps with the peak of each pulse above the pacemaker's interference threshold, the pacemaker will inhibit (cut off). If the effective PRR is greater than some inherent value (specific to each device), the pacemaker may revert to its interference rejection mode (fixed rate). Reversion to fixed rate is judged nonhazardous. Inhibition is judged hazardous.

(4) Proximity and orientation of the pacemaker patient with respect to the incident EMR field. Body shielding can significantly alter the EMI, particularly at frequencies greater than 1 GHz. In many cases of interference such as those associated with microwave ovens (2450 MHz), the user can completely eliminate the EMI by simply rotating his or her body 90° - 180° to place more body shielding between the pacemaker and the EMR source. Also, pacemakers exhibit immediate recovery to normal function as soon as the EMR signal is eliminated.

(5) State-of-health and cardiac condition of the user. Some users are much more or less dependent on exact pacemaker function and may or may not be able to tolerate the transient effects of EMI.

Currently marketed pacemakers exhibit a wide range of EMI susceptibilities, demonstrating the technical feasibility of manufacturing devices to be compatible with most EMR environments. In general, the pacemakers being marketed today as compared to those of two years ago offer considerably more resistance to electromagnetic interference. Also, it appears the total number of the more sensitive pacemakers in service two years ago has been reduced about 80%. Continuing effort by the manufacturers will ultimately resolve most of the potential pacemaker EMI problems, and it is hoped that the manufacturers of other medical instrumentation and electronic prostheses will incorporate good EMI rejection techniques in all new devices.

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ON EMP SAFETY HAZARDS

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SUMMARY

The only two quantitative criteria presently available for setting of electromagnetic pulse (EMP) safety standards are: (1) the ANSI C95.1 Safety Standard based on limiting thermal insult at microwave frequencies, and (2) the thresholds for the stimulation of excitable membranes by electric current. The first is not realistic for application to the EMP since the induced currents and energy deposition in exposed tissue is not based on an applied field amplitude and duration relationship, but is related only to the rise and fall time of the applied field pulse. The induced currents in the tissues of man exposed to impulsive electromagnetic (EM) fields do not appear to be sufficient for stimulating action potentials.

A. INTRODUCTION

There has been recent concern over the hazards of electromagnetic pulse (EMP) simulators designed to simulate the EMP emanating from a nuclear explosion. These simulators are used for testing electronic control and communication equipment for performance under the environment of a nuclear attack. Generally, the simulators are designed to generate a transient high intensity electromagnetic field (EM) with an electric field intensity in excess of 50 kV/m and a field impedance of 120π ohms. The rise times and pulse widths of such EM pulses are in the order of nanoseconds. Frequently, in order to evaluate the possible safety hazards to operating personnel and the general population in the vicinity of such devices, the generated fields have been compared to fields emanating from lightning flashes, static discharges and power line corona [1]. The incident average power flux density of recurring EMP fields has also been compared to the microwave safety standards of 10 mW/cm^2 in order to show that the EMP power flux currently generated by simulators is orders of magnitude below that which would be a thermal threat to man [2]. Currently, the only guidelines available that are based on substantial scientific justification pertaining to the exposure of man to EM or currents are the ANSI C95.1 Standard [3], and the guidelines pertaining to electrical shock [4], [5].

The ANSI Standard limits the incident power flux density to 10 mW/cm^2 as averaged over any six minute period and is based principally on the limitation of tissue heating to negligible values at microwave frequencies. The electrical shock criteria, on the other hand, limits the current to levels that prevent various undesirable physiological effects relating to the stimulation of excitable cells. For macroshock with a 1 second contact period with a 60 Hz source, these levels are 1 ma for the threshold of perception, 5 ma for maximum harmless current intensity, 10-20 ma for "let-go" current before sustained muscular contraction, 50 ma for pain, possible fainting, and mechanical injury, 100-300 ma for ventricular fibrillation, and 6000 ma for sustained myocardial contraction, followed by normal heart rhythm, temporary respiratory paralysis, and burns.

If we limit the EMP exposure level by the ANSI Standard, we must satisfy the relation

$$\frac{r}{120\pi} \int_0^\infty |e(t)|^2 \, dt \leq 100 \text{ J/m}^2 \tag{1}$$

where r is the pulse rate with a value no less than 1 pulse/6 minute period, and e(t) is the electric field strength of the EMP as expressed in the time domain.

The EMP exposure level may also be limited by the maximum allowable current induced in the body. Since the induced current is considerably different in character to that due to 60 Hz shock, a rationale is needed to extropolate the known results for the latter to the case of the extremely short pulse of current induced by an EMP source. It has been shown that the minimum fibrillating currents from a 60 Hz source may be expressed as $I = k/t^{1/2}$ ma where k is a constant and t is the period of applied current [4]. This relation was tested for t as low as 0.01 seconds, or approximately one-half cycle.

Past studies and experiments indicate ventricular fibrillation is unlikely if the shock current is less than

$$I = 116/t^{1/2} \text{ ma} \tag{2}$$

This would also imply that

$$I = 5/t^{1/2} \text{ ma} \tag{3}$$

would be safely below the threshold of the "let-go" current. According to Schwan [6], the current density, J, in the tissues for producing ventricular fibrillation is approximately 1 ma/cm^2, and that for producing excitation of excitable membranes is in the order of 0.1 - 1.0 ma/cm^2, so

for the threshold of tissue interaction for 60 Hz currents.

For extremely short direct current pulses, the strength-duration relation for the stimulation of excitable membranes may be expressed as

$$J_s = J_m \, t_m/t \tag{5}$$

where J_m is the minimum excitation current density, t_m is the time constant of the cell membrane, and J_s is the peak stimulation current density (7). If we assume that the current density predicted by Equation (3) for a half cycle or 1/120 seconds is the minimum excitation current and consider a typical membrane time constant of 10^{-3} seconds we can combine Equations (4) and (5) to give

$$(10^{-3})t^{-1} \leq J_s \leq (10^{-2})t^{-1} \ \mathrm{ma/cm^2} \tag{6}$$

Equation (6) may be expressed in terms of the total charge density transfer in the time T as

$$(10^{-2}) \leq \int_0^T J(t)\, dt \leq (10^{-1}) \ \mathrm{coulombs/m^2} \tag{7}$$

where J(t) is the current density in the time domain.

B. FIELD COUPLING EQUATIONS

In general, the (time domain) electric field, e(t), and magnetic field h(t), of the EMP consists of a narrow pulse with a very rapid rise time, t_m, in the order of 5 to 10 nanoseconds and with a field impedance of 120π ohms. The pulse width, t_o, may be defined in the standard way as

$$t_o = \frac{1}{e(t_m)} \int_0^\infty e(t)\, dt. \tag{8}$$

In order to develop insight on what the coupling of the EMP may be to biological tissues in the body of man or smaller animals, we may first make a rough approximation by considering its coupling to an equivalent spherical mass of muscle-type material previously analyzed for exposure to RF plane waves by Lin, et al. (8), and then extrapolate the results to the figure of an actual man based on absorbed power density patterns measured by thermography. The total electric field induced in the sphere, $\bar{E}_s$, by an incident plane wave with an electric field strength E_i at an angular frequency of ω is

$$\bar{E}_s = E_i \, e^{j\omega t} \left[\frac{3}{\epsilon_t^*} \hat{x} - j\frac{kR}{2} (\cos\phi \, \hat{\theta} - \cos\theta \sin\phi \, \hat{\phi})\right]$$

where $\epsilon_t^* = \epsilon_t - j\frac{\sigma_t}{\omega\epsilon_o}$ is the complex dielectric constant of the tissue, k is the propagation constant for free space, ϵ_t is the relative dielectric constant of the tissue, σ_t is the electrical conductivity of the tissue, and ϵ_o is the permittivity of free space. The origin of the (x,y,z) and (R,θ,φ) coordinate systems corresponds to the center of the sphere with the direction of plane wave propagation coincident with the z axis, and the electric field coincident with the x axis. The first term (x component of the above equation) may be interpreted to be the uniform field in the sphere induced by the incident electric field component and the remaining θ and φ terms can be interpreted to be that induced by the incident magnetic field component. The equation is accurate for a 70 kg, 25.6 cm radius sphere of muscle tissue up to 20 MHz in frequency and for smaller spheroids approximating the head of man or small animal bodies beyond 100 MHz in frequency. In the RF frequency range the value of dielectric constant ϵ_H is significantly smaller than the loss factor, so we may make the approximation $\epsilon_H^* \approx j\frac{\sigma_H}{\omega\epsilon_o}$ where σ_H is assumed to be constant over the frequency range of interest.

It then follows that for incident EMP transient fields from lightning or other impulsive sources with rise times sufficiently long or with a frequency spectrum limited to a range where the equations are valid, the (frequency domain) electric field $\bar{E}_s(\omega)$ induced in a spherical body of tissue is

$$\bar{E}_s(\omega) \approx j\frac{E(\omega)}{2c} \, \omega \, \bar{F}(R,\theta,\phi) \, e^{j\omega t} \tag{10}$$

where E(ω) is the magnitude of the incident field and

$$\bar{F}(R,\theta,\phi) = \left[\frac{\hat{x}}{20\pi\sigma_t} - R(\cos\phi \, \hat{\theta} - \cos\theta \sin\phi \, \hat{\phi})\right] \tag{11}$$

The induced field $e_s(t)$ may be expressed in time domain as

$$\bar{e}_s(t) = \frac{1}{2c} \, \bar{F}(R,\theta,\phi) \, \frac{de(t)}{dt} \tag{12}$$

Thus, under the stated frequency restrictions, the field strength induced in the spherical tissue model is directly proportional to the time rate of change of incident field. It is also clear that the major components of the induced field are the $\hat{\theta}$ and $\hat{\phi}$ terms of $\bar{F}(R,\theta,\phi)$ corresponding to an induced circulating eddy current. This can be seen by noting that the x component $\frac{1}{20\pi\sigma_t} = 2.65 \times 10^{-2}$ is an order of magnitude smaller than the maximum value (2.56×10^{-1}) of the induction field component for a typical tissue conductivity of $\sigma_t = 0.6$ mho/m and a radius R = 25.6 cm for a 70 kg sphere of muscle-type tissue. According to this approximate analysis, the normalized field distribution induced in the sphere along the three major rectangular axes is

shown in Fig. 1. The electric field distribution along the y axis is that due to the electric field coupling and the other distributions along the y and z axes are influenced mostly by the magnetically induced eddy current which is proportional with distance from the y axis.

The instantaneous absorbed power density in the spherical tissue muscle is

$$P = \sigma_H e_s^2(t), \tag{13}$$

the current density is

$$J(t) = \sigma_H e_s(t), \tag{14}$$

the absorbed energy density is

$$W = \int_0^\infty P dt, \tag{15}$$

and the transferred charge density in time is

$$\rho = \int_0^T J(t)\, dt = \sigma_H \int_0^T e_s(t) dt \tag{16}$$

For comparison purposes, consider a transient EM field given by

$$e(t) = E_0(e^{-\alpha t} - e^{-\beta t}) \tag{17}$$

which may be used to represent the EMP or lightning by appropriate choice of values of α and β.

For this case the pulse rise time is

$$t_m = \frac{\ln(\beta/\alpha)}{\beta-\alpha}, \tag{18}$$

the induced electric field is

$$\bar{e}_s(t) = \frac{E_0}{2c} \bar{f}(R,\theta,\phi)[\beta e^{-\beta t} - \alpha e^{-\alpha t}], \tag{19}$$

the pulse width is

$$t_0 = \frac{\beta-\alpha}{\alpha\beta} (e^{-\alpha t_m} - e^{-\beta t_m})^{-1}, \tag{20}$$

the absorbed energy density is

$$W = \frac{\sigma_t E_m^2 |\bar{f}(R,\theta,\phi)|^2 (\beta-\alpha)^2}{8c^2(\beta+\alpha)(e^{-\alpha t_m} - e^{-\beta t_m})^2} \tag{21}$$

and the transferred charge density in time T is

$$\rho = \frac{\sigma_H E_m}{2c} |\bar{f}(R,\theta,\phi)| \frac{[e^{-\alpha T} - e^{-\beta T}]}{e^{-\alpha t_m} - e^{-\beta t_m}} \tag{22}$$

where

$$E_m = E_0(e^{-\alpha t_m} - e^{-\beta t_m}) \tag{23}$$

is the peak incident field strength.

The above equations should provide rough estimates of the characteristics of fields induced in the equivalent muscle sphere if $\omega = \beta$ or α is sufficiently small for Equation (4) to be valid. For the 25.6 cm sphere according to Lin, et al. [8], Equation (4) is valid only to 20 MHz. The calculated value is about 60% too high at 80 MHz and 80% too high at 100 MHz. For smaller diameter spheres corresponding to smaller animals or portions of the human body such as the head, the equation should be valid well above 100 MHz.

Fig. 1 illustrates the induced electric field and energy density patterns in a sphere exposed to an impulsive EM field where the spectrum is within the above limitations. Typical EMP and lightning field coupling can be determined from the above equations by an appropriate choice of α and β. Table I illustrates computed characteristics restricted according to Equation (1) for r = 1, and values of α and β appropriate for simulating the various fields.

It should be pointed out from our previous discussion that the coupled internal field for the EMP could be as high by as much as a factor of 2 and the absorbed power and energy density could be as high by as much as a factor of 4, as calculated by the above equations, since with $\beta = 4.76 \times 10^8$, the upper end of the spectrum exceeds $\beta/2\pi \approx 80$ MHz. The results will show, however, that the error is of no consequence for the "ball park" estimates desired in this analysis. The time dependence of the maximum coupled fields (periphery of sphere) due to fast rise and slow rise time lightning fields is shown in Fig. 2 and that due to the typical EMP is shown in Fig. 3.

The results for a sphere may be extrapolated to the case of a man exposed to the free field of an EMP from the thermographic measurements described in another section of this Lecture Series "Engineering Considerations and Measurements" Section D (6). The results show that maximum absorption of a sphere is 0.36 W/kg for a magnetic field of 1 A/m at 24.1 MHz. This would correspond to 1.05 μW/kg for a sphere exposed to a plane wave with electric field strength of 1 V/m at 31 MHz. On the other hand, there would be a maximum absorbed power density of 134 μW/kg in a man exposed to the same field.

Thus the maximum absorbed power density is 128 times greater and the maximum current density is 11.3 times greater for the man in the region of his legs. Thus we can increase the parameters in Table I by these factors to estimate the EMP coupling to man. The same factors would be as high as 28 and 5.3, respectively, in other regions of the body such as the neck and the rib cage.

C. DISCUSSION

By the restrictions of the ANSI safety guide as given by Equation (1), tabulated in Table I and illustrated in Figs. 1 and 3, relatively slow rise time fields such as originating from lightning would be limited to produce less than 1 ma/cm^2 peak current densities in spherical tissue structure while a relatively fast rising field such as the EMP would produce nearly 7 amperes/cm^2 peak current density in the tissue. The pulse width has very little to do with the maximum induced current and the maximum absorbed energy density. Figs. 2 and 3 and Table 1 clearly point out that it is the rise time, t_m, of the field that is most important in terms of the magnitude of the induced current, peak absorbed power density, and the energy density deposition. There are 4 to 5 orders of magnitude greater field strength coupling, 8 to 10 orders of magnitude greater peak absorbed power density, and 4 to 5 orders of magnitude greater peak absorbed energy density for the sphere exposed to the EMP than for exposure to lightning fields. It is clear that the error in the approximate analysis is inconsequential in terms of using the results to illustrate the large difference in coupling characteristics of the transient field.

The first row of data in Table I corresponds to coupling due to a typical fast rise and fall time EMP. The ANSI standard criteria would allow an incident field strength of 530 kV/m which would induce a current of 7 amperes/cm^2 in a spherical structure or 80 amperes/cm^2 in an exposed man in free space. The peak absorbed power would be as high as 7.6 megawatts/kg in the sphere or 973 megawatts/kg in man. Though this seems unusually high, the brevity of the pulse restricts the total deposited energy to 8 mJ/kg for the exposed sphere, 1.03 J/kg for the legs, and 253 mJ/kg for the neck of an exposed man. Note that the absorbed energy levels are above that required to produce the microwave auditory effect (16 mJ/kg) discussed in this Lecture Series "Microwave Induced Acoustic Effects in Mammalian Auditory Systems." The total charge transfer during the period corresponding to a membrane time constant is nil due to the biphasic property of the induced current. Thus we would not expect membranes to be directly stimulated. However, if we consider the EMP with a slow fall time, with properties as illustrated in the second row of Table 1, there would be a net change transfer of 9.47 x 10^{-7} coulombs/m^2 for the sphere and 1.07 x 10^{-6} coulombs/m^2 for man since during the period corresponding to the membrane time constant the produced current is predominantly the same polarity. Note, however, for this case the pulse width safety criteria would limit the incident field to 5.5 kV/m. The total charge transfer would be insufficient to produce excitation of action potentials. Even if the man was exposed to the maximum incident field strength of 330 kV/m allowed by the ANSI safety standard for a pulse rate of no greater than 1 per 6 minute period, it appears that the induced charge transfer would be orders of magnitude below that necessary to stimulate action potentials based on the simple model.

The third and fourth rows of Table 1 give the coupling characteristics of EM fields produced by lightning. The induced currents and absorbed power densities are considerably less than induced by the EMP due to the substantially greater rise times in the former. Table 1 also illustrates the typical coupling characteristics for microwave pulses to the tissue sphere based on a single pulse per second restricted by Equation (1). The coupling may be derived from an analysis by Johnson and Guy [9]. Most of our experience with continuous human exposure, however, has been limited to situations involving microwave pulses with recurrence rates of many tens or hundreds of pulses per second with the average incident power density restricted to 10 mW/cm^2, or less. The coupling characteristics for this case are shown at the bottom of Table 1. Note that the induced current, absorbed power and absorbed energy densities are substantially higher than values produced by the EMP.

The coupling equations and Fig. 1 illustrate that much less coupling would occur in smaller diameter tissue structures exposed to transient fields. The distributions in Fig. 1 may be truncated to the appropriate radius to determine the reduction in coupling. For example, the maximum coupled field would be 0.26 times less and the maximum energy absorption density would be .07 times less for a 5 cm radius sphere representing a small animal.

CONCLUSIONS

The above analysis shows that without considerable qualification, one should not depend wholly on experience gained from the exposure of man to lightning fields or from small animals exposed to the EMP fields as a guide for establishing safety standards. Also, for impulsive fields such as the EMP, more attention should be given to the rate of change of field rather than the width or peak amplitude of the field in establishing safety standards. It appears unlikely that action potentials can be excited in man exposed to plane wave type EMP fields.

TABLE I CHARACTERISTICS OF EMP, LIGHTNING, AND PULSED MICROWAVE FIELDS COUPLED TO 70 kg MAN EQUIVALENT SPHERE WITH FIELD STRENGTHS RESTRICTED BY ANSI C95.1 SAFETY CRITERIA (EQUATION 1) FOR ONE PULSE PER SECOND

PULSE CHARACTERISTICS AND (SAFETY CRITERIA)	α	β	RISE TIME t_m(s)	PULSE WIDTH t_o(s)	MAX INC. FIELD STR. e(V/m)	MAX RATE OF e CHG. $\frac{de}{dt}$ (V/m·s)	MAX CURRENT DENSITY J_m (ma/cm^2)	$\int_0^{10^{-3}} J(t)dt$ COULOMBS/m^2	PEAK ABSORBED POWER DENSITY P(W/kg)	PEAK ABSORBED ENERGY DENSITY W(J/kg)
EMP	4.00×10^{6}	4.76×10^{8}	10^{-8}	2.60×10^{-7}	5.30×10^{5}	2.63×10^{14}	6.76×10^{3}	0	7.61×10^{6}	7.92×10^{-3}
EMP	4.00×10^{2}	4.76×10^{8}	2.90×10^{-8}	2.50×10^{-3}	5.49×10^{3}	2.61×10^{12}	6.73×10^{1}	9.47×10^{-7}	7.54×10^{2}	7.92×10^{-7}
LIGHTNING	1.10×10^{5}	3.30×10^{5}	5.00×10^{-6}	1.58×10^{-5}	6.07×10^{4}	3.47×10^{10}	8.93×10^{-1}	0	1.33×10^{-1}	1.51×10^{-7}
LIGHTNING	5.41×10^{4}	8.11×10^{4}	1.50×10^{-5}	4.16×10^{-5}	3.66×10^{4}	6.69×10^{9}	1.72×10^{-1}	0	4.94×10^{-3}	1.83×10^{-8}
MICROWAVES SINGLE 2.60×10^{-7} SEC. PULSE/SEC 2.45 GHz			10^{-10}	2.60×10^{-7}	5.38×10^{5}	8.28×10^{15}	2.25×10^{4}	0	2.31×10^{7}	6.00
MICROWAVES 100 2.60×10^{-7} PULSES/SEC 2.45 GHz			10^{-10}	2.60×10^{-7}	5.38×10^{4}	8.28×10^{14}	2.25×10^{3}	0	2.31×10^{5}	6.00×10^{-2}

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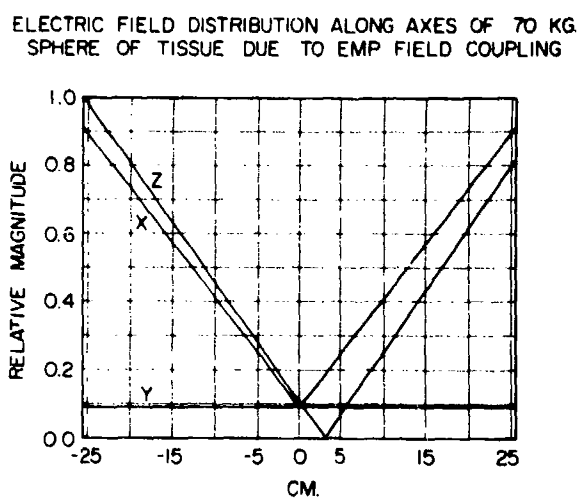
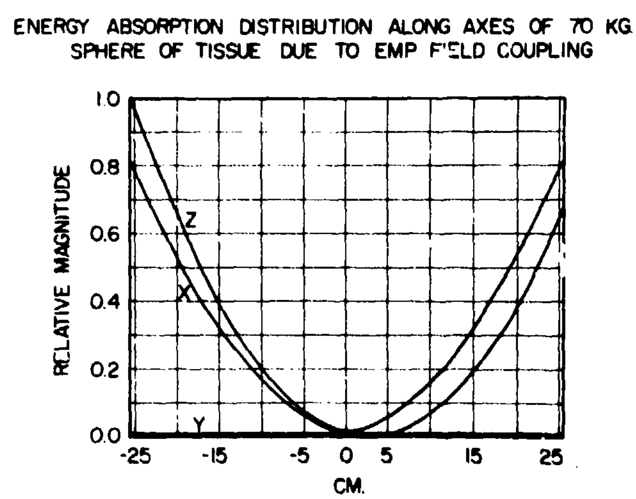
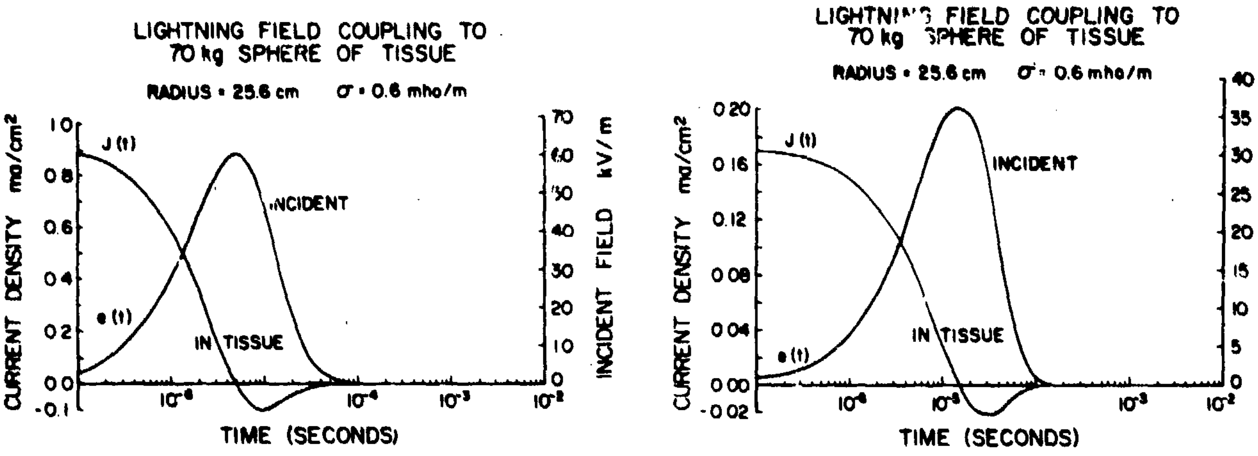


(a)



(b)

Figure 1 Approximate normalized electric field strength and energy density distribution along major axes in 70 kg sphere of tissue exposed to EMP field.



(a) Fast Rise Time (b) Slow Rise Time

Figure 2 Lightning field coupling to exposed tissue sphere with field limited by equation (1).

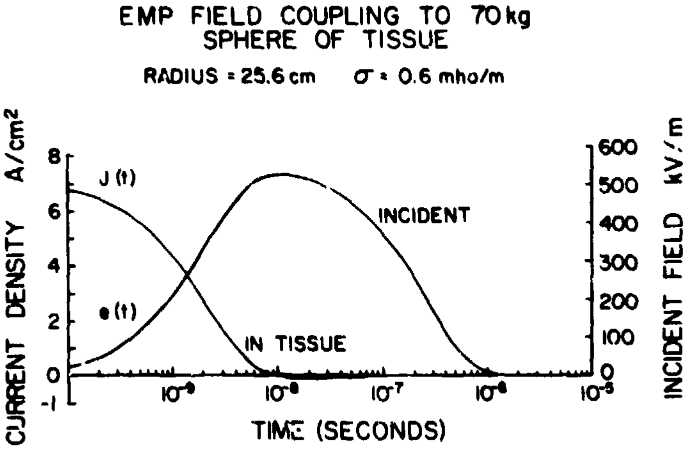


Figure 3 EMP field coupling to sphere of exposed tissue with field limited by equation (1).

Protection Guides and Standards for Microwave Exposure

by

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INTRODUCTION

Many of the electromagnetic energies at certain frequencies, power levels and exposure durations can produce biological effects or injury depending on multiple physical and biological variables. Although equipment which utilize or emit electromagnetic energy provide immeasurable benefits to mankind, they may also constitute hazards to the individual through uncontrolled and excessive emissions. There is a need to set limits on the amount of exposure to radiant energies individuals can accept with safety.

Protection standards should be based on scientific evidence but quite often are the result of empirical approaches to various problems reflecting current qualitative and quantitative knowledge. A numerical value for a standard implies a knowledge of the effect produced at a given level of stress, and that both effect and stress are measurable. One problem is the definition of what an "effect" is and whether it can ultimately be shown to modify man's "way of life" or that of his offspring (1).

If there were a clear-cut relationship between exposure level and pathophysiologic effect, the problem of setting standards would be greatly simplified. Not only are there numerous variables to be considered, but it is often difficult or impossible to obtain the necessary data to draw valid conclusions concerning effects of exposure to noxious agents.

In most biological processes, there is a certain range between those levels that produce no effects and those that produce detectable effects. A detectable effect is not necessarily one that is irreparable or even a sign that the threshold for damage has been reached. Ultimately, a clear differentiation has to be made between biologic effects per se which do not result in short term or latent functional impairment against which the body cannot maintain homeostasis and effectiveness, and injury which may impair normal body activity.

In considering standards, it is necessary to keep in mind the essential differences between a "personnel exposure" standard and a "performance" standard for a piece of equipment. An exposure standard refers to the maximum safe (incorporating a safety factor) level of power density and exposure time for the whole body or any of its parts. This standard is a guide to people on how to limit exposure for safety. An emission standard (or performance standard) refers not to people but to equipment and specifies the maximum limit of emission close to a device which ensures that likely human exposure will be at levels considerably below personnel exposure limits.

To insure uniform and effective control of potential health hazards from microwave exposure, it is necessary to establish uniform effect or threshold values. Ideally, effect or threshold values should be predicated on firm human data. If such data are not available, however, extrapolation from well-designed, adequately-performed and properly analyzed animal investigations is required.

EPIDEMIOLOGIC STUDIES AND CASE REPORTS

A number of retrospective studies have been done on human populations exposed to microwave energy. These have been, for the most part, either radar operators and repairmen or personnel involved in production and testing of microwave equipment, primarily radar. The studies may be divided into essentially two categories: those seeking general effects, and those specifically seeking changes in the lens of the eye.

Daily (2) conducted the first studies on United States Navy personnel who were exposed over a period of time in the operation and testing of relatively low power radar. No evidence of radar-induced pathology was found. Lidman and Cohn (3) examined the blood of 124 men who had been exposed to microwaves for periods from two to 36 months. They concluded there was no evidence of stimulation or depression of erythropoiesis or leukocytopoiesis. A decade later, Barron, Love and Baraff (4, 5) reported on a large group of radar workers who, along with a control group, were put under a four-year surveillance program. During this period, they underwent repeated physical, laboratory, and eye examinations. The examinations failed to detect any significant changes in the physical inventories of the subjects.

A paper by La Roche et al (6) of a study by Zaret reports "ophthalmic microwave injury" in 33 employees in an Air Force base. It is important to note that the authors themselves state, "...however, since preemployment examinations do not normally include examination specifically for microwave injury, there is either limited or no information available concerning the prior condition of the lens." Also, of these 33 individuals, only 4 were negative at the initial examination. One, therefore, has no means of relating the results of the examination to previous history. Most important, the authors state, "...it is not certain if those persons showing evidence of microwave injury on first examination actually received the exposure while working on the Air Force" base.

No cases of "microwave cataracts" have been described in the Polish literature (7). A higher incidence of lenticular opacities was reported in groups with histories of uncontrolled exposure (8) and may possibly be related to poorly controlled exposure conditions. It should be noted that published case reports of microwave cataract in man have not been adequately subjected to editorial review and reported in the open literature. Even the most quoted case reports of Hirsch and Parker (9) and Shimkovich and Shilyayev (10) have not established a cause and effect relationship. The validity of these claims has not been accepted by most ophthalmologists and microwave bioeffects experts.

Epidemiologic studies were initiated in the USSR in 1957 to determine the extent of the health hazards for workers with exposure to RF or microwaves (11). Workers were examined after separation into 3 groups, according to exposure levels (12).

1. Periodic exposure to "high energy density" levels, i.e. 0.1-10 mW/cm^2 and higher beginning in 1953 (13);
2. Periodic exposure to "low energy density" levels, i.e. 0.01-0.1 mW/cm^2; these individuals commenced work a... 1960 when the Soviet standard was largely in force;
3. Systematic exposure to low energy density levels.

The first group consisted of production, technical maintenance and microwave equipment repair personnel. Many of these were periodically exposed to near-zone fields. The second group consisted of technical maintenance personnel as well as certain categories of personnel engaged in the use of microwave apparatus, research workers and others. The third group consisted of personnel engaged in the use of various microwave sources, mainly radar.

The clinical picture of the first two groups was characterized by the presence or absence of "restorative" processes (13), and functional changes in the nervous system and cardiovascular system. Individuals in the third group showed few changes which could be differentiated from those in the control group and consequently could not be related to their microwave exposure (13).

In a study reported by Czerski and associates (7, 14) and Siekierzynski et al (15) an analysis of the incidence of disorders considered as contraindications for occupational microwave exposure among 841 males aged 20 to 45 years and exposed occupationally to microwaves for various periods was made. The analysed population was subdivided into two groups differing only in respect to microwave exposure - low, i.e. below 0.2 mW/cm^2 and high, i.e. between 0.2 mW/cm^2 and 6 mW/cm^2. No dependence of the incidence of disorders to be considered contraindications for occupational exposure could be demonstrated. The incidence of lenticular opacities was compared between both these groups, as well as analysed within each group, subdivided according to age or duration of occupational exposure. No dependence of the incidence of lenticular opacities on the exposure level, nor on duration of occupational exposure was found. Significant correlation with age was demonstrated. The incidence of functional disturbances (neurotic syndrome, gastrointestinal tract disturbances, cardiovascular disturbances with abnormal ECG) was also analysed and no dependence on the exposure level or duration of occupational exposure (years) could be demonstrated (7).

A very cogent analysis of the problems in occupational surveys has been made by Czerski and Siekierzynski (7) who noted that analysis of occupational exposure to microwave radiation is fraught with many difficulties, the main being the assessment of the relationship between the microwave exposure levels and the health status of the examined groups of workers. The possible role of other environmental factors and of socio-economic conditions must be taken into account. As often happens in clinical work, it is difficult to demonstrate a causal relationship between a disease and the influence of environmental factors, at least in individual cases. Large groups must be observed to obtain statistically significant epidemiological data. The problem of adequate control groups is controversial and hinges mostly on what one considers "adequate." In view of the lack of adequate instrumentation, especially of individual "dosimeters," the quantitation of occupational exposure is extremely doubtful. This is particularly true where personnel move around in the course of their duties and are exposed to nonstationary fields (i.e., moving beams or antenna), as well as to near- and far-fields at random. It is impossible to quantitate the exposure over a period of several years within reasonable limits. Attempts to present detailed data as to the source of microwave radiation, effective area of irradiation, position of the body with respect to the field, etc. for an individual worker for a period of several years would be misleading to an extreme degree.

PERSONNEL EXPOSURE STANDARDS

Microwave exposure standards are generally based, with some variations, on those developed in the U.S., USSR, Poland, and Czechoslovakia. The original U.S. standard was tentatively adopted about 20 years ago on the basis of theoretical considerations by Schwan and his associates. This standard was based on the "thermal load" that a standard (healthy) adult man could tolerate and dissipate under standard environmental conditions without any resulting rise in body temperature. This tolerance level was calculated to be 10 mW/cm^2 for continuous exposure. Intensive investigation was subsequently carried out by the U.S. Department of Defense into the biological effects of microwave radiation (16). None of these investigations produced any evidence for a biological effect at levels even approaching the theoretical limit of 10 mW/cm^2, and, indeed, no conclusive evidence was established for any effect below the level of 100 mW/cm^2 that could be considered hazardous for man (16).

The United States standard (ANSI C95.1) of 10 mW/cm^2 for radiofrequency exposure recommended in 1966 and reaffirmed in 1973 is at least a factor of ten below thresholds of damage by thermal effects, assuming a long duration of exposure--i.e., one quarter hour or more. The 10 mW/cm^2 level is based on thermal equilibrium conditions for whole-body exposure. For normal environmental conditions and for incident electromagnetic energy of frequencies from 10 MHz to 100 GHz, the radiation protection guide is 10 mW/cm^2, and the equivalent free-space electric and magnetic field strengths are approximately 200 V/m RMS and 0.5 A/m RMS, respectively. For modulated fields, power density and the squares of the field strengths are averaged over any 0.1 hour period, i.e. none of the following levels should be exceeded as averaged over any 0.1 hour period: Electric Field Strength Squared - 40,000 V^2/m^2; 0.25 A^2/m^2; Power Density - 10 mW/cm^2; Energy Density - 1 mWh/cm^2; this guide applies whether the radiation is CW or intermittent and applies to the general public as well as workers.

The value of 10 mW/cm^2 has been generally accepted by industry and the armed services in the United States and is considered to be the population standard. The British adopted the 10 mW/cm^2 level for the general public as well as the military and industry after careful consideration by many government and independent organizations (17). Sweden, in 1961, after an extensive review of all the information available, recommended "the maximum permissible intensity (average irradiation) within areas where personnel are occasionally to be found is 10 mW/cm^2 for all occurring frequencies" (18). The Federal Republic of Germany, France, and N.V. Phillips in the Netherlands have also established 10 mW/cm^2 as a maximum safe level (19, 20). The standards recommended in various countries are shown in Table I and figure 1.

The ANSI C95.1 standard does not specify an upper limit of allowable short-time exposure. It specifies a safe value based on average dose for a period of 0.1 hour. According to this standard, no individual should be exposed without good reason to a power density in excess of 10 mW/cm^2 for a time period longer than 6 minutes. On this basis, it permits continuous exposure to a level averaging 10 mW/cm^2; momentary levels in excess of this are allowable if the energy density does not exceed 1 mWh/cm^2.

While the limit of 10 mW/cm^2 served as a practical exposure level in the U.S. Department of Defense for several years, it was felt that the duration of exposure was important and that higher levels could be tolerated for shorter periods. A guide was developed, therefore, and published in 1965: Exposure of personnel within a microwave field (300 to 300,000 MHz) is permitted only for a specified length of time determined by the following equation:

$$T_p = 6000/X^2$$

where T_p = permissible time of exposure in minutes during any 1-hour period, and X = power density (mW/cm^2) in the area to be occupied. Because exposures of less than 2 minutes are operationally impractical, the use of this formula for power densities above 55 mW/cm^2 is contraindicated.

TABLE I

Personnel Exposure Standards for Microwaves

Maximum Permissible Power Density (mW/cm^2)	Frequency (MHz)	Country or Agency	Specifications
10	10-100,000	U.S.*	
		ANSI	1 mWh/cm^2, 24h
		NIOSH	8 h workday
	100-100,000	ACGIH	10 mW/cm^2 TLV - 8 h 10-25 mW/cm^2, 10 min/h 25 mW/cm^2 - ceiling value
	300-300,000	Army/Air Force	10-55 mW/cm^2 min = 6000/$(mW/cm^2)^2$
1	300-300,000	Poland	0.2 mW/cm^2-10 mW/cm^2 (8 h - 11.5 s) (SF)** 1.0 mW/cm^2-10 mW/cm^2 (8 h - 4.8 min) (NSF)
		USSR***	15-20 min/day
0.1		Poland	0.2 mW/cm^2, 8 h (SF) 24 h (NSF)
		USSR	2-3 h/day
0.025		Czechoslovakia	8 h (CW)
0.01		Poland	24 h (SF)
		USSR	8 h
		Czechoslovakia	8 h (pulsed)

*Also with slight modification - Canada, United Kingdom, German Federal Republic, Netherlands, France, Sweden.
**SF = stationary field (hr = 32/W/m^2);NSF = nonstationary field (hr = 800/W/m^2).
***MPE x 10 for exposure to movable beam or antenna.

The American Conference of Governmental Industrial Hygienists (ACGIH) has published threshold limit values (TLV) for the frequency range of 100 MHz to 100 GHz. The TLV for occupational microwave energy exposure where power densities are known and exposure time is controlled is as follows: 1) For average power density, levels up to but not exceeding 10 mW/cm^2, total exposure time shall be limited to the 8-hour workday (continuous exposure); 2) For average power density levels from 10 mW/cm^2 up to but not exceeding 25 mW/cm^2, total exposure time shall be limited to no more than 10 minutes for any 60-minute period during an 8-hour workday (intermittent exposure); 3) For average power density levels in excess of 25 mW/cm^2, exposure is not permissible (ceiling value).

In regard to performance standards, a product emission standard for microwave ovens has been established in the U.S. This standard specifies a maximum level of 1 mW/cm^2 at 5 cm from the external surface of the oven at manufacture and a maximum of 5 mW/cm^2 at 5 cm from the external surface of the oven throughout the life of the product.

In respect to the ANSI C95.1 standard, results of more than two decades of laboratory and clinical investigations indicate no adverse changes in the state of health of individuals, even after many years of exposure to microwaves within the specified limits. Although we need more data relative to the total energy that can be absorbed by man without adverse effect, analysis of the state of health of individuals occupationally exposed for 15 to 20 years to microwave radiation levels ranging from several to more than 10 mW/cm^2 indicates that additional precautions are unnecessary (16, 21).

Until recently, microwave personnel exposure standards for most of the Eastern European countries have been based, with minor variations, on limits established by the USSR. These limits, promulgated in 1959 by the USSR Ministry of Health, specify maximum safe exposure for an unlimited period of time at 0.01 mW/cm^2 (10 $\mu W/cm^2$); 0.1 mW/cm^2 (100 $\mu W/cm^2$) exposure is permitted for a period of 2 hours in a 24-hour period; up to 1 mW/cm^2 for 20 minutes in a 24-hour period. Permissible exposure is ten times as great for radiation emanating from equipment with a movable beam or antenna (22). In addition, levels of exposure differing by an order of magnitude are permissible because of possible field gradients and limits of accuracy of measuring instruments(12). The USSR has also adopted a maximum electrical field intensity level for electromagnetic radiation of frequencies below the microwave band.

It is of interest that the Soviets do not consider microwave cataractogenesis of any serious consequence at low exposure levels. The Soviet experience in the area of microwave bioeffects has been summarized in a book from the Academy of Medical Sciences of the USSR edited by Petrov (22).

A search of the Soviet literature fails to reveal substantiation for limiting exposure time to 2 hours or 20 minutes in a 24-hour period to levels of 100 and 1000 $\mu W/cm^2$, respectively Petrov and Subbota (23) suggest the basis for the Soviet standard is the reports noting that some disturbances occur in experimental animals at exposure levels in the vicinity of 1 mW/cm^2. Taking this value as a limiting value and considering a full workday as rounded off to 10 hours they arrived at a permissible exposure level of 0.1 mW/cm^2. Introducing an additional safety factor of 10, they come up with a level of 0.01 mW/cm^2 (10 $\mu W/cm^2$). In general it would appear that the values obtained in this manner from experimental studies indicate a large

safety factor and can be applied to the general population, but it seems that these values are too conservative for personnel subjected to periodic medical examination such as in the industrial setting (21).

In 1972, Poland departed from the Soviet standard on the basis of an extensive study, over a 15-year period, of a large number of civilian and military personnel occupationally exposed to various levels of microwaves from 1 to more than 15 years. During this study no instances of irreversible damage or disturbances caused by exposure to microwave radiation were encountered. Any disturbances and deviations from normal were those of a functional nature. Medical examinations conducted several months after removal from occupational exposure to microwave radiation indicated a reversal of disturbances. A group of selected subjects, who were examined in detail during a 5-year period of observation, were found to be healthy even in instances where permissible radiation levels were exceeded (21).

Under the new Polish standard (figure 1) the Poles differentiate between stationary fields, continuous irradiation at a given point, such as a work station or personnel position, and interrupted irradiation at such a point, designated as nonstationary fields. On the basis of these principles, they have differentiated safe, intermediate, warning, and danger zones, where the boundaries of the individual zones are determined by measuring average energy levels in the bands from 300 to 300,000 MHz in watts per square meter.

The following zone boundaries are proposed for stationary fields:

1. Safe zone - the highest level of energy shall not exceed 0.1 W/m^2 (0.01 mW/cm^2).
2. Intermediate zone - the boundary values of radiation level shall be 0.1 W/m^2 (0.01 mW/cm^2) at the lower boundary and 2 W/m^2 (0.2 mW/cm^2) at the upper boundary.
3. Warning zone - the lower and upper boundary levels shall be 2 W/m^2 (0.2 mW/cm^2) and 100 W/m^2 (10 mW/cm^2).

The following levels are proposed for nonstationary fields:

1. Safe zone - the maximum permissible level shall not exceed 1 W/m^2 (0.1 mW/cm^2).
2. Intermediate zone - between 1 W/m^2 and 10 W/m^2 (0.1 mW/cm^2 to 1 mW/cm^2).
3. Warning zone - between 10 W/m^2 and 100 W/m^2 (1 mW/cm^2 to 10 mW/cm^2).
4. Danger zone - energy levels greater than 100 W/m^2 (10 mW/cm^2).

Permissible time for a worker in a danger zone is determined by the formula:

$$\text{Stationary field} \quad t = 32/p^2$$

$$\text{Nonstationary field} \quad t = 800/p^2$$

where t = time in hours, and p = average radiation level in watts per square meter.

CONCLUSION

The development of adequate and operable standards requires comprehensive evaluation of information obtained from animal experiments and surveys of individuals exposed occupationally. The criteria to be used in evaluating experimental results of microwave exposure and the interacting variables in such assessment requires the exercise of informed judgement. Since there are variations in the criteria used in many countries, these have to be understood and evaluated.

Guides and exposure levels in force today appear to be entirely safe. So far, there is no documented evidence of injury to military or industrial personnel or the general public from the operation and maintenance of radars and other RF and microwave emitting sources within the 10 mW/cm^2 limit of exposure.

There is no evidence of hazard to man from RF and microwaves under normal conditions of operation and exposure. Nevertheless, concern has been aroused about the safety of personnel in intense RF fields close to transmitting antennas operating in the frequency bands below 30 MHz. Such environments are in general of a near-field type which precludes the measurement of power flux. Since hazard evaluation in this frequency range is a function of measurement in the near-field, attention should be paid to the problems inherent in such measurement.

The divergences between US and East European standards are, to a great degree, due to differences in basic philosophy -- differences which appear in industrial hygiene and basic scientific research. The standard used in the US and most other countries is, as already noted, based on the amount of exogenous heat which the body could tolerate and dissipate without any resulting rise in body temperature. This tolerance level was calculated to be 10 mW/cm^2 for continuous exposure. In contrast with US standards, the USSR maximum permissible exposures are based on "asthenia" syndromes reported by workers in the microwave field.

There is no evidence in western world scientific literature that the present US standard of 10 mW/cm^2 represents a hazardous exposure level. If the general philosophy of industrial hygiene in the United States is considered, that for every "toxic substance" there exists a concentration or level below which no injurious effects will result and that not all "effects" represent "hazards," this position becomes even more sound.

According to Magnuson et al (24), the industrial hygiene philosophy of the USSR basically consists of: 1) The maximum exposure is defined as that level at which daily work in that environment will not result in any deviation in the normal state as well as not result in disease. 2) Standards are based entirely on presence or absence of biological effects without regard to the feasibility of reaching such levels in practice. 3) The values are maximum exposures rather than time-weighted averages. 4) Regardless of the value set, the optimum value and goal is zero. Maximum permissible exposure (MPE) values are not rigid ceilings but, in fact, excursions above these values "within reasonable limits" are permitted and the maximum permissibles represent desirable values for which to strive rather than absolute values to be used in practice. In view of the basic differences in industrial hygiene philosophy, it does not appear that the standards used in the US and USSR are as irreconcilable as would appear.

Well designed and appropriately controlled epidemiologic and clinical investigations of groups of workers and others exposed to microwaves should be fostered. Studies of workers and individuals exposed to microwaves or RF along with appropriate control groups, should include a thorough analysis of the exposure environment, including average power density, peak power density, frequency, and pulse repetition rate. It should be noted that epidemiological studies have in the past attempted to show effects but without clear indication of actual power levels and duration of microwave exposure. This has resulted in widespread uncertainty and confusion concerning the safe RF and microwave exposure levels for humans.

Epidemiologic surveys based on prospective study and analysis of exposed human populations balanced by appropriately matched controls should use a well designed comprehensive standardized protocol using the most modern analytical tools and computer-based statistical techniques. Data on groups of exposed persons, for whom sufficient physical information on the exposure level is available, such as in therapeutic use of microwave diathermy, should be collected to provide a basis for future epidemiological and other studies.

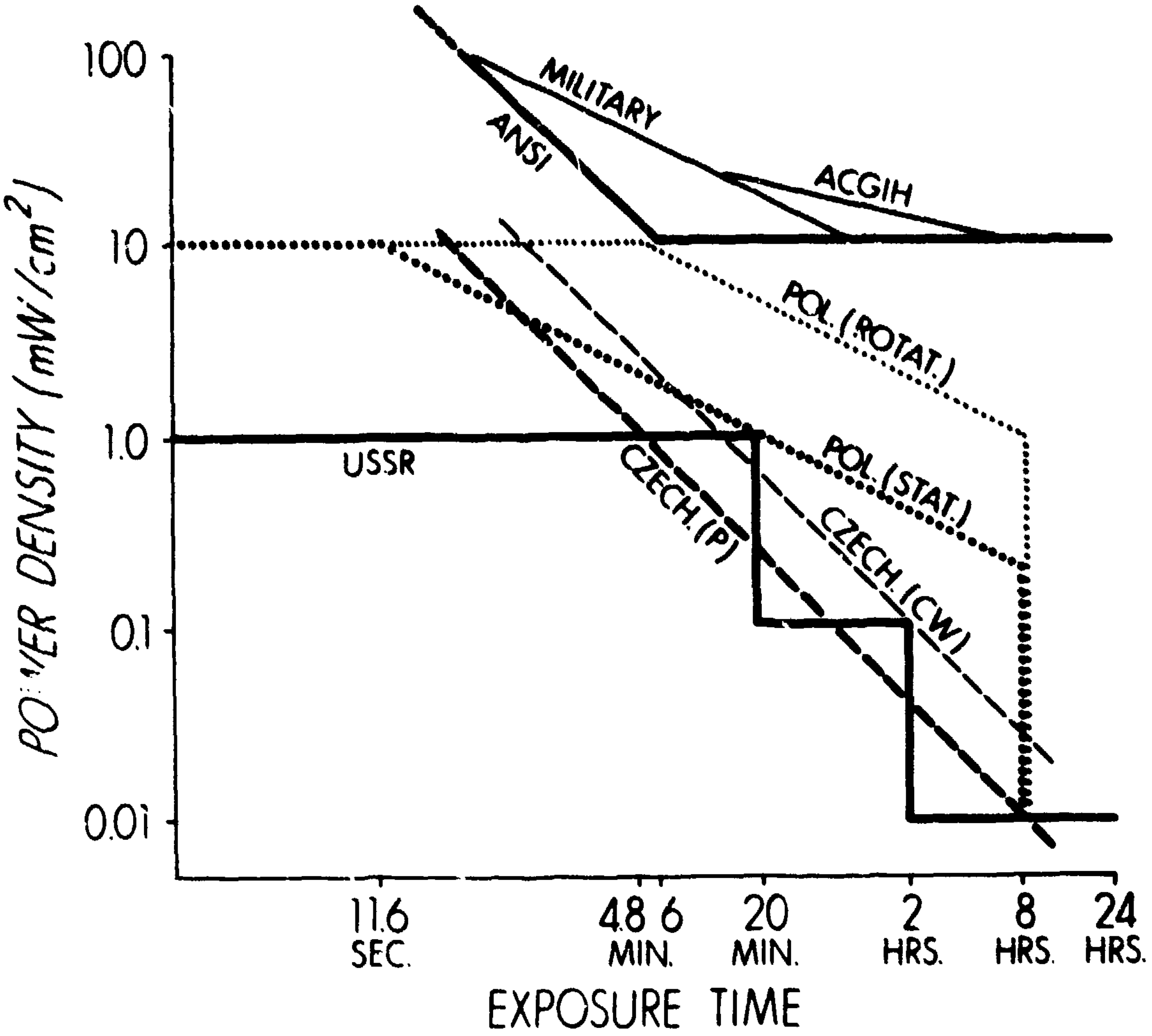

FIGURE 1. Microwave Personnel Exposure Standards.

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Biologic Effects of Microwaves, Radiofrequency and Ultrasound

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Washington, D. C.

Section 1.

MICROWAVES: Documents of Major Importance

75-00001
BIOLOGIC EFFECTS AND HEALTH HAZARDS OF MICROWAVE RADIATION
Polish Med Publ Warsaw 1975 1 p Proc of an Intern Symp Warsaw 15 18 Oct 1973

75-00002 United States of America Standards Inst New York
SAFETY LEVEL OF ELECTROMAGNETIC RADIATION WITH RESPECT TO PERSONNEL
9 Nov 1966 1 p
(USAS C95)

Recommendations for protection of workers against the harmful effects of exposure to electromagnetic radiations in the frequency range 10 MHz to 100 GHz are made. Permissible radiation level under normal environmental conditions is indicated as follows power density 10 milliwatts per square centimeter for periods of 0.1 hour or more energy density 1 milliwatt hour per square centimeter during any 0.1 hour period. Attention is drawn to the relationship between body temperature circulatory disorders and environmental heat stress and radiation damage.

75-00003 Bureau of Radiological Health Rockville Md
REGULATIONS FOR THE ADMINISTRATION AND ENFORCEMENT OF THE RADIATION CONTROL FOR HEALTH AND SAFETY ACT OF 1968
Jul 1974 1 p
(DHEW FDA 75 8003)

The Radiation Control for Health and Safety Act was signed by the President on October 18 1968. The purpose of this Act was to protect the public from unnecessary exposure to radiation from electronic products. Radiation covered in the Act was called electronic product radiation and was defined to mean any ionizing or nonionizing electromagnetic or particulate radiation or any sonic infrasonic or ultrasonic wave which is emitted from an electronic product as the result of the operation of an electronic circuit in such product. The provisions of the Act give the Secretary Department of Health Education and Welfare authority to establish and carry out an electronic product radiation control program which shall include performance standards for electronic products. The regulations contained herein have been promulgated under that authority. The Bureau of Radiological Health is responsible for the day to day operation in carrying out the Act's mandate for an electronic product radiation control program. A principal objective of the program is to protect the public health through setting and enforcing electronic radiation emission performance standards. This compilation is revised periodically and efforts are made to provide an accurate reproduction of the regulations up to the data of this publication. his publication contains those regulations published in the FEDERAL REGISTER through April 20 1974. To maintain current information on amendments or deletions to 21 CFR Subchapter J and for the official regulations the reader should consult the latest issuances of the FEDERAL REGISTER and the Code of Federal Regulations Title 21.

75-00004
MEDICAL CONSIDERATIONS OF EXPOSURE TO MICROWAVES (RADAR)
C I Barron and A A Baraff 1 Nov 1958 1 p Reprinted from J of Am Med Assoc 1968 p 1194 1199

In 1954 a medical surveillance program was instituted covering 335 employees working with or exposed to microwaves in an airframe manufacturing company. Examinations were performed at intervals of 6 12 and 24 months in an effort to detect acute or cumulative biological effects of exposure at various intervals to energized radar beams in the 400 to9 000 mc range and with peak power output exceeding one megawatt. Whenever possible identical examinations were also accomplished on a nonexposed control group. The examinations failed to detect any significant changes in the physical inventories of the subjects. The incidence of death and chronic disease sick leave and subjective complaints was comparable in both groups. A high percentage of eye pathology was identified but none with causal relation to the hyperthermia produced by microwave absorption. Fertility studies revealed essentially the same findings for both groups. Laboratory studies for total red and white blood cell counts and differential counts revealed no significant changes above those noted in the control group. Urinalyses and chest X rays were noncontributory with respect to radar exposures. Electrophoretic serum protein level determinations were performed on 26 subjects with insignificant or accountable deviations in 10. Platelet counts and controlled capillary fragility studies for Pumpel Leede phenomenon revealed the fallacy of using either to identify radar exposure. In addition only a small percentage of the exposed subjects were aware of heat or other subjective warning phenomena. Neither these tests nor subjective complaints were considered reliable indexes of exposure. Absolute or safe maximum exposure standards were impossible to define inasmuch as no radar induced pathology could be identified. The need for more precise and refined exposure data is indicated. On the basis of these studies there appears to be no justification for public concern about the effects of greatly attenuated microwave energy in the environment.

75-00005
THE ACTION OF MICROWAVE RADIATION ON THE EYE
R L Carpenter and C A VanUmmersen 1969 1 p refs
Repr from J Microwave Power (Canada) v 3 1969 p 3 19

Microwave power can cause formation of opacities in the lens of the rabbit eye exposed to continuous wave or pulsed wave radiation at frequencies from 2.45 GHz to 10 GHz. When the eye is irradiated in a free field the opacity (cataract) develops in the posterior part of the lens. In location form and growth it resembles cataracts caused by ionizing radiation. When the eye is irradiated at the same frequencies as part of a closed waveguide system the cataract develops in the anterior part of the lens like those caused by infrared radiations. Although for every power level there is a minimal exposure period which will cause an opacity repeated shorter exposures can have a cumulative effect the main determining factor being the time interval between successive exposures. Experimental evidence suggest that microwave cataracts are not simply a result of microwave heating but are caused by some other property of the radiation.

75-00006 Bureau of Radiological Health Rockville Md
BIOLOGICAL EFFECTS AND HEALTH IMPLICATIONS OF MICROWAVE RADIATION. SYMPOSIUM PROCEEDINGS
Stephen F Cleary ed Jun 1970 2 p Symp held at Richmond 1969 sponsored by Medical Coll of Va Va Commonwealth Univ and Bureau of Radiological Health
(DBE 70 2)

The primary goal of the Symposium on the Biological Effects and Health Implications of Microwave Radiation was to provide an indication of the present state of the art in this area. The proceedings are a compilation of the 31 technical papers presented the deliberations that followed each one and the two panel discussions that concluded the meeting. Since there is a great deal of uncertainty concerning the effects of low intensity microwave and radio frequency radiation on the mammalian central nervous system a concerted effort was made to include a comprehensive presentation of various aspects of this problem. The majority of the CNS effects on humans were reported by scientists from the U S S R and Eastern European nations. The

rate of progress in the unraveling of the unknown factors in microwave-exposure effects will undoubtedly depend to a significant extent upon the development of new concepts and methods for the quantification of microwave and radio frequency fields. To this end, an attempt was made to unveil new measurement parameters as a possible means of reducing the uncertainty presently encountered in this field. The need for improvements in the presently existing measurement techniques is underscored by the complex nature microwave and radio frequency devices which increase the difficulty of power density measurements. The related problem of measurements standards and standardization of the methods of reporting microwave of RF exposure parameters used in biological research is of great concern since, at present, the intercomparison of the data of different investigators studying similar biological effects is in many cases rendered difficult if not impossible. The discussion of the present situation and suggestions for remedies for these difficulties presented in the symposium serve as an impetus for the development of the necessary standards.

76-00007
BIOLOGICAL EFFECTS OF MICROWAVE RADIATION AND POSSIBLE RISKS FROM RADAR
C J Clemedson 1961 1 p Repr from T Milt Halsov (Sweden) no 86 1961 p 69

76-00008
CATARACTS AND ULTRA-HIGH-FREQUENCY RADIATION
D G Cogan, S F Fricker, and M Lubin 1958 1 p Repr from Arch Indust Health, v 18, 1958 p 299-302

Ultrahigh frequency radiation (at 468 MHz) was repeatedly applied to rabbits in doses near the lethal level. Rabbits were exposed in three groups. Group A received 60 mW/sq cm during 20 to 30 min once weekly for 5 to 7 weeks. Group B was irradiated daily (except in the weekends) for a total of 10 exposures at 60 mW/sq cm during 20 min. Group C received 10 exposures at the rate of 2 exposures a week, the power density was 60 mW/sq cm for 15 min in 5 animals, and 30 mW/sq cm for 90 min in 4 animals. The radiation was distributed over the whole body. No cataracts developed following the exposures.

76-00009
THE PAIN THRESHOLD FOR MICROWAVE AND INFRA-RED RADIATIONS
H F Cook 1952 1 p refs Repr from Brit J Physiol (England), v 118, 1952 p 1-11

A method of evoking thermal pain by a microwave stimulus (10 cm, 3000 MHz) is described and the results obtained on normals reported. These show that the skin temperature at which pain is felt is independent of all variable factors. On the other hand, the radiation intensity (or so called pain threshold) depends on exposed area, exposure time, initial skin temperature, anatomical site and thermal conductivity. An equation based on thermal flow theory is given which explains satisfactorily the results obtained with short exposures to microwaves. Extension of the theory to explain the results of workers using infrared pain stimuli is also successful. Consideration of the tolerated intensities of three types of thermogenic radiation leads to the result that the energy absorption in the first 1-2 mm of superficial tissues is the same for all radiations, if other factors are constant. It is further suggested that a vital factor on which thermal pain is dependent is the temperature of end-organs located within this depth of tissue. Criticism of the Hardy-Wolff-Goodell method of thermal pain study is made. It is suggested that, besides the measurement of initial and end-point skin temperatures, the observation of the rate of increase of skin temperature would be of value in providing information regarding thermal conductivity. The question of spatial summation of pain and warmth senses is discussed very briefly.

76-00010
PROPOSALS FOR SPECIFICATION OF ALLOWABLE LEVELS OF MICROWAVE RADIATION
P Czerski and M Piotrowski 1972 1 p Repr from Medycyna Lotnicza (Poland), no 39, 1972 p 127-139

The U S and Soviet standard radiation levels allowable for humans are discussed, including substantiation of these levels. Polish standards for permissible exposure to microwave radiation are also presented.

76-00011
SOVIET RESEARCH ON THE NEURAL EFFECTS OF MICROWAVES
C Dodge and S Kassel Nov 1966 1 p (AD-645979, ATD-66-133)

Soviet open sources published from 1962 to 1966 with a few published earlier are reported. Soviet research is outlined on the effect of low intensity microwave radiation on the central nervous system of living organisms, including man. There are six sections: scope of efforts, including organizations and individual researchers, subject development, specific neural functions and structures, in vivo effects, neural effects of low frequency electromagnetic and magnetic fields, and clinical, therapeutic and hygienic aspects. Each of these sections may be read independently. The discussion summarizes important facts and deductions and speculates on the intensity and type of Soviet research efforts in this area in the future. The bibliography includes 42 entries.

76-00012
CLINICAL AND HYGIENIC ASPECTS OF EXPOSURE TO ELECTROMAGNETIC FIELDS: A REVIEW OF SOVIET AND EASTERN EUROPEAN LITERATURE
C H Dodge 1970 3 p refs Repr from Biol Effects and Health Implications of Microwave Radiation, 1970 p 140-149

It is suggested that a wide variety of neurological and physiological reactions are to be expected during exposure to nonthermal (i.e., less than 10 mW/sq cm) field intensities within an extremely wide range of frequencies (approximately 30-300,000 MHz). These reactions, which are generally reversible, are often documented as a result of human exposure to field intensities as low as a few microwatts/sq cm. They are reported to be primarily effects upon the nervous system and reflect traditionally heavy Soviet emphasis on the central nervous system. Soviet and East European findings in this area are therefore in striking contrast to those of the West which have, in the main, documented non-CNS responses to thermal (i.e., greater than 10 mW/sq cm) intensities. Only in the realm of human endocrine, visual, and skin receptor responses to thermal microwave burdens is any real substantive agreement between Soviet and Western findings to be found. The substantially lower Soviet and East European daily maximum permissible dose (MPD) value for human exposure to microwave radiation appears to be based upon extensive findings of human subjective and other CNS-related responses to extremely low microwave field intensities and upon considerable CNS-oriented research on animals conducted in these countries. These findings also indicate that extensive dosimetric surveys around industrial and military sources of microwave radiation were conducted in those countries.

76-00013
HEATING CHARACTERISTICS OF LABORATORY ANIMALS EXPOSED TO TEN-CENTIMETER MICROWAVES
T S Ely, D E Goldman, and J Z Hearon Oct 1964 1 p refs Reprinted from IEEE (Inst Elec Electron Engr), Trans Bio-Med Eng, v 11, Oct 1964 p 123-137

Experimental animals were exposed to a 10-cm microwave field in order to study the heating and cooling characteristics of the entire animal and localized sensitive structures. The flanks of rats, rabbits and dogs were exposed and the whole body heating was observed. After heating, the cooling curve was determined. Similarly, restricted area fields were used to study heating and cooling of eyes and testes. Data on the heating and cooling rates were used to determine the most sensitive structures. The experimental findings, together with the values for some pertinent related factors from the literature, provide the basis for an estimation of the possible risks to man from exposure to microwaves.

76-00014
RADIATION EFFECTS ON THE EYE

W J Geeraets Oct 1970 1 p Reprinted from Ind Med Surg v 39 Oct 1970 p 441 450

The effects of five types of radiation namely ionizing ultraviolet near infrared far infrared and microwaves on the eye are discussed The radiation in these regions poses potential dangers to the human eye against which protection and control are of high importance Dangers of overexposure are discussed with suggested permissible exposure levels

78-00015 Naval Medical Research Inst Bethesda Md
BIBLIOGRAPHY OF REPORTED BIOLOGICAL PHENOMENA (EFFECTS) AND CLINICAL MANIFESTATIONS ATTRIBUTED TO MICROWAVE AND RADIO-FREQUENCY RADIATION SUPPLEMENT NO 4 MEDICAL RESEARCH
Interim Report
Z R Glaser Jun 1973 1 p
(AD 770621)

More than 325 additional references on the biological responses to radio frequency and microwave radiation published up to May 1973 are included in this bibliography of the world literature Particular attention has been paid to the effects of non-ionizing radiation on man at these frequencies The citations are arranged alphabetically by author and contain as much information as possible so as to assure effective retrieval of the original documents Soviet and East European literature is included

78-00016 Israel Program for Scientific Translations Ltd Jerusalem
BIOLOGICAL EFFECT OF MICROWAVES IN OCCUPATIONAL HYGIENE
Z V Gordon 1970 1 p Transl into ENGLISH of the book Voprosy Gigieny Truda i Biologicheskogo Deistviya Elektromagnitnykh Polei Sverkhvysokikh Chastot Leningrad Izd Vo Med Press 1966 Sponsored by NASA and NSF
(NASA TT F 633 TT 70 50087)

Results of years of investigations in collaboration with laboratory personnel in the fields of occupational hygiene and biological effects of radio frequency electromagnetic irradiation are generalized for the range of superhigh frequencies (SHF) Emphasis has been placed on the occupational hygiene of personnel working with SHF sources and on protection against detrimental effects established by clinical and experimental investigations

78-00017
BIOLOGICAL EFFECTS OF RADIO FREQUENCY ELECTROMAGNETIC FIELDS, NO. 4
Z V Gordon 1973 1 p Repr from a Russian J no 4 (Moscow) p 7 14
(JPRS 63321)

78-00018
ANALYSES OF ELECTROMAGNETIC FIELDS INDUCED IN BIOLOGICAL TISSUES BY THERMOGRAPHIC STUDIES ON EQUIVALENT PHANTOM MODELS
A W Guy Feb 1971 1 p refs Repr from IEEE (Inst Elec Electron Eng) Trans V MTT 19 no 2 Feb 1971 p 205 214

One of the most vexing problems in studies involving the interaction of electromagnetic fields and living biological systems and tissues is the quantification of the fields induced in the tissues by nearby sources This paper describes a method for rapid evaluation of these fields in tissues of arbitrary shape and characteristics when they are exposed to various sources including plane wave aperture slot and dipole sources The method valid for both far and near zone fields involves the use of a thermograph camera for recording temperature distributions produced by energy absorption in phantom models of the tissue structures The magnitude of the electric field may then be obtained anywhere on the model as a function of the square root of the magnitude of the calculated heating pattern The phantoms are composed of materials with dielectric and geometric properties identical to the tissue structures which they represent The validity of the technique is verified by comparing the results of the experimental approach with the theoretical results obtained for the case of plane layers of tissue exposed to a rectangular aperture source and cylindrical layers of tissue exposed to a plane wave source This technique has been used successfully by the author for improving microwave applicators

78-00019 Medical Biological Lab RVO TNO Rijswijk (Netherlands)
SUMMARIES, BIOLOGICAL EFFECTS OF MICROWAVE RADIATION. PART 6: ABSTRACTS ON MICROWAVE RADIATION EFFECTS ON HUMAN AND ANIMAL PHYSIOLOGICAL FUNCTIONS AND LIFE EXPECTANCY
H Heering and P M M Vanosch May 1972 1 p
(MBL 1972 6, TDCK 59854 Pt 6)

Abstracts on the biological effects of microwave radiation on humans and animals are presented Data cover hemodynamic responses biological rhythm changes, muscular reflexes eye sight decrement, and various other physical damages and effects on life expectancy of exposed individuals

78-00020
CUTANEOUS RECEPTOR RESPONSE TO MICROWAVE IRRADIATION
E Hendler 1968 1 p Repr from Thermal Problems in Aerospace Med, 1968 p 149 161

Differences in conductive and volumetric tissue heating were investigated in an attempt to elucidate the mechanism of cutaneous warmth sensation to microwave irradiation The forehead was selected as the area for study, subjects were university students and laboratory personnel of both sexes It was found that both infrared and microwave stimuli that were capable of evoking threshold sensations produced a temperature increase of between 0 01 and 0 02 C of the layer lying 200 microns deep over that located 1000 microns below the surface Analysis of the infrared data indicated that the threshold of warmth sensation could be correlated with a temperature rise of about 0 02 C occurring about 200 microns below the surface of the skin

78-00021 Washington Univ, Seattle
NONIONIZING ELECTROMAGNETIC WAVE EFFECTS IN BIOLOGICAL MATERIALS AND SYSTEMS
C C Johnson and A W Guy Jun 1972 1 p Repr from IEEE (Inst Elec Electron Eng), v 60, Jun 1972 p 692 718
(NIH 8 RO1 RL00528 02, NIH GM 16436, NIH-GM 16000)

Consideration of the problem of microwave penetration into the body with resultant internal power absorption from both the theoretical and experimental viewpoints The results are discussed in terms of therapeutic warming of tissues and possible hazards caused by internal hot spots The absorption and scattering effects of light in biological tissues are reviewed Molecular absorption peaks in the optical spectrum are useful for making molecular concentration measurements by spectroscopy Much of the related work in the literature is summarized, some new results are presented, and several useful applications of wave energy and medical instruments are discussed

78-00022
PHYSIOLOGIC HAZARDS OF MICROWAVE RADIATION: A SURVEY OF PUBLISHED LITERATURE
H Kalant 1959 1 p Repr from Can Med Assoc J, v 81, 1959 p 575 582

After dealing with the physical characteristics and transmission of microwave radiation (MWR), and the mechanisms of microwave energy conversion in tissues, experimental lesions produced by MWR and the quantitative aspects of microwave hazards are reviewed The biological significance of nonthermal effects of MWR is discussed

78-00023 National Aeronautics and Space Administration, Washington D C
THE EFFECT OF ELECTROMAGNETIC AND MAGNETIC FIELDS ON THE CENTRAL NERVOUS SYSTEM

Yu A Kholodov 1966 1 p Transl into ENGLISH from Russian Publ
(NASA TT-F 465)

The physiological mechanism of the effect of electromagnetic fields (EMF) on the functions of the brain was studied using electrophysiological and conditioned reflex methods. Various methods of recording motor activity and determining the sensitivity to electrical and chemical stimuli and morphological methods are described. The experimental animals were different classes of vertebrates beginning with fish and ending with mammals.

78-00024
THE BIOLOGICAL ACTION OF ULTRAHIGH FREQUENCIES
A A Letavet and Z V Gordon 1960 1 p Repr from Acad of Med Sci (Moscow) 1960

78-00025
SHORT AND ULTRASHORT WAVES IN BIOLOGY
P Liebesny Urban and Schwarzenberg Vienna 1935 1 p

78-00026
RADIATION CATARACTOGENESIS
S Lorman 1962 1 p refs Repr from New York State J of Med v 62 1962 p 307 308

The eye is unusually sensitive to many forms of the two major types of radiation the electromagnetic spectrum and corpuscular radiation. Radio waves, long wave diathermy and visible rays usually do not produce cataracts but short wave diathermy and infrared and ultraviolet radiation have a definite cataractogenic potential. While grenz rays beta radiation and cosmic rays may produce cataracts, they are of little significance in comparison with other forms of radiation cataractogenesis. Neutrons roentgen rays and gamma rays possess the most serious cataractogenic potential. The cataracts produced by these three forms of radiation are similar in appearance and structure consisting initially of posterior subcapsular and cortical opacities requiring latent periods before becoming visible and occurring with doses that do not necessarily produce any other clinically evident lesions. One of the earliest chemical changes observed in the lens following exposure to X radiation is a rapid fall in the level of SH (sulfhydryl) groups. Experiments on rats have suggested that the initial direct effects of X radiation of the lens may be due to its action on RNA (ribonucleic acid) and DNA (desoxyribose nucleic acid) within the lens.

78-00027
QUESTIONS ON THE APPLICATIONS OF MICROWAVES AND ULTRASONIC WAVES IN MEDICINE [VOPROSY PRIMENENIYA KOROTKIKH I ULTRAKOROTKIKH VOLN V MEDITSINE]
N N Malov Moscow 1940 1 p In RUSSIAN

78-00028
PHYSIOLOGICAL EFFECTS OF THERMODE AND MICROWAVE STIMULATION OF PERIPHERAL NERVES
R D McAfee 1962 1 p refs Repr from Amer J Physiol v 203 no 2 1962 p 374 378

Physiological effects produced in cats dogs rabbits and rats by microwave irradiation (3 cm radar and 12 2 cm Microtherm) are duplicated in these animals by heating peripheral nerves with a warm water or resistance wire thermode. Identical effects occur when a temperature ranging between 45 47 C is attained by either of these means at a treated peripheral nerve or within tissue rich in peripheral nerve fibers. The response elicited by thermode or microwave stimulation includes arousal reactions, blood pressure and vascular responses, and signs of neurohumoral activity. It was demonstrated that the physiological effect of microwave radiation is a result of thermal stimulation of peripheral nerves which occurs independently of a significant increase in skin temperature or of total body heating.

78-00029
ANALYSIS OF REPORTED PHYSIOLOGIC EFFECTS OF MICROWAVE RADIATION
R D McLees and Ed Finch 1973 1 p Repr from Eng ADV Biol Med Phys v 14 1973 p 163 223

78-00030
ELECTROMAGNETIC FIELDS AND THE LIFE ENVIRONMENT
K Marha, J Musil and H Tuha 1971 1 p Transl into ENGLISH from Czechoslovakian Publ

The primary purpose of this text is to make known to physicians and electronic engineers the fundamental problems encountered in evaluating the possible effects of radio waves on living matter, with particular emphasis on man and the protection of the human organism against such effects. An understanding of basic concepts of mathematics, physics, biology, and chemistry is necessary. The biological effects of electromagnetic waves and their mechanisms, the occurrence and use of electromagnetic energy, the maximum permissible field intensity and radiation and their determination, health and technical problems involved in working with generators of electromagnetic waves, and the organization of working conditions are considered. An appendix describes a standard method of determining field intensity and electromagnetic wave irradiation in the RF and UHF ranges for health purposes.

78-00031
THE TRI-SERVICE PROGRAM: A TRIBUTE TO GEORGE M. KNAUF, USAF (MC)
S M Michaelson Feb 1971 2 p refs Repr from IEEE (Inst Elec Electron Eng) Trans v MTT-19, no 2 Feb 1971 p 131 146

During World War II the Department of Defense medical services became interested and concerned about possible hazards associated with the development, operation, and maintenance of the increasing numbers of radars and other radio-frequency emitting electronic equipment. After some investigations by the U S Navy and the U S Air Force, responsibility for research on the biomedical aspects of microwave radiation was delegated in July 1957 as a tri service arrangement to Rome Air Development Center Griffiss Air Force Base, N Y. Primary responsibility for coordination of the program rested with Dr George M Knauf, USAF (MC). The Tri-Service Program included investigation of effects of exposure of the whole body, selected organs and tissues, single cells, and enzyme systems using various power levels, pulsed and continuous wave, in the frequency spectrum from 200 through 24 500 MHz under acute, subacute, and chronic conditions. The most important contribution of the Tri-Service Program was the validation of the 10 mW/sq cm safety standard. The Tri-Service Program is to date the only large scale coordinated effort in the Western world to elucidate and understand some of the basic mechanisms of microwave bioeffects and to assess possible health implications of this form of energy. This paper constitues an overview of the Tri-Service Program to provide some historical insight into the significance of the program and its contributions to our understanding of the biologic effects of microwaves.

78-00032
BIOMEDICAL ASPECTS OF MICROWAVE EXPOSURE
S M Michaelson May 1971 1 p Repr from Eng AM Ind Hyg Assoc J v 32, May 1971 p 338 345

78-00033 Rochester Univ., N Y
BIOLOGICAL EFFECTS OF MICROWAVE EXPOSURE: AN OVERVIEW
S M Michaelson 1972 1 p Repr from J Microwave Power (Canada), v 6, no 3, 1971 p 259-267

An important effect of microwave absorption is found to be the conversion of the absorbed energy into heat. It was found that the exposure of various species of animals to wholebody microwave radiation at levels of 100 mW/sq cm or more is characterized by a temperature rise, a function of the thermal regulatory processes and active adaptation of the animal. The end result is either reversible or irreversible, depending on the irradiation conditions and the physiological state of the animal. Thermal responses in dogs are characterized by initial thermal response, a period of thermal equilibrium, and a period of thermal

breakdown In areas in which relatively little blood circulates the temperature rises considerably (since there is little means for the interchange of heat), and tissue damage is more likely to occur

75-00034 Rochester Univ., N.Y.
HUMAN EXPOSURE TO NONIONIZING RADIANT ENERGY. POTENTIAL HAZARDS AND SAFETY STANDARDS
S M Michaelson Apr 1972 1 p Repr from IEEE (Inst Elec Electron Eng), v 60, apr 1972 p 389-421 Sponsored by AEC
The pathophysiology is discussed of exposure to ultraviolet, infrared coherent electromagnetic (laser), microwave, and radio-frequency radiation Biomedical aspects of exposure are considered along with the organs most susceptible to damage and the human tolerance threshold for radiation. Protection guidelines established for the different types of radiation are summarized along with difficulties in formulating them

75-00035 Rochester Univ., N.Y.
CUTANEOUS PERCEPTION OF MICROWAVES
S M Michaelson Jun 1972 1 p Repr from J of Microwave Power (Canada), v 7, Jun 1972 p 67-73 Sponsored by AEC
Results of studies indicate that when a 40 sq cm area of the face is exposed to microwaves, thermal sensation can be elicited within 1 sec at power densities of 21 mW/sq cm for 10 000 MHz, and 58 6 mW/sq cm for 3000 MHz Within 4 sec, the threshold is lowered by approximately 50% Thresholds for pain reaction of the inner forearm were also studied The data indicate that microwave sensation may provide a protection factor against exposure to microwaves at levels that could be injurious

75-00036
SOVIET VIEWS ON THE BIOLOGICAL EFFECTS OF MICROWAVES: AN ANALYSIS
S M Michaelson and C H Dodge Jul 1971 1 p Repr from Eng Health Phys., v 21, Jul 1971 p 108-111

75-00037
SOME TECHNICAL ASPECTS OF MICROWAVE RADIATION HAZARDS
W W Mumford 1961 1 p Repr from Proc IRE, v 49, 1961 p 427-447
The potential hazards of microwave power to man is discussed along with adopted safety measures Research work which has influenced the establishment of criteria for safe and potentially hazardous environments for human beings is reviewed The currently adopted safety limits are described and a recommended method of calculating power densities is derived. Commercially available power density meters are mentioned and their method of operation is described along with their use in surveying a site The shielding effect of wire mesh fences is presented in a monograph

75-00038
RADIO FREQUENCIES AND MICROWAVES. MAGNETIC AND ELECTRICAL FIELDS
Yu I Novitskiy, Z V Gordon, A S Presman, and Yu A Kholodov Washington NASA 1971 1 p
(NASA-TT-F-14021)

75-00039
BIOPHYSICAL FOUNDATIONS OF THE THERAPEUTIC ASPECTS OF HIGH FREQUENCY ELECTRICAL FIELDS
J Paetzold and H. B Schaefer 1948 1 p Repr from Nat. Sci Med in Germany, 1934-1946, Vol 22, Biophys 2, Wiesbaden, 1948 p 17-19

75-00040 Scripta Technica, Inc., Washington, D.C.
INFLUENCE OF MICROWAVE RADIATION ON THE ORGANISM OF MAN AND ANIMALS
I R Petrov, ed Feb. 1972 1 p Transl into ENGLISH of the book "Vliyaniye Svch Izlucheniya na Organizm Cheloveka i Zhivotnykh" Leningrad, Meditsina Press, 1970
(Contract NASw-2038)
(NASA-TT-F-708)
The effect of the microwave field on the organism were studied The biological bases of the action of microwave electromagnetic radiation on the organism are considered with experimental material on the influence of high and low microwave intensities on the animal organism, characterizing the functional changes of the organism's basic systems and its metabolism Damage due to microwaves combined with other factors and changes in the organism's immunological reactivity, the properties of bacteria, viruses, and simple animals were discussed The influence of microwaves on the human organism and data acquired as a result of observations on volunteers as to the influence of low microwave intensities on the healthy human organism are studied along with the symptomatology, stages, reversibility of changes, and a classification for the pathological processes that arise under the influence of microwaves in persons working with microwave generators.

75-00041
PROCEEDINGS OF THE FOURTH ANNUAL TRI-SERVICE CONFERENCE ON THE BIOLOGICAL EFFECTS OF MICROWAVE RADIATION
M F. Peyton, ed. 1961 1 p
(RADC-TR-60-180)
The biological effects of microwave radiation on human pathology, metabolism, development, neurology and the biomedical aspects of microwave radiation are discussed in various papers Major areas included are the following the radiofrequency environment, microwave instrumentation for the measurement of biological effects, generation and detection of pulsed X-rays from microwave sources; engineering aspects of microwave radiation hazards, development of a garment for protection of personnel; and thermal effects of high-frequency fields.

75-00042
ELECTROMAGNETIC FIELDS AND LIFE
A. S Presman Plenum, New York 1970 1 p Transl into ENGLISH from the Russian

75-00043
RESULTS OF BIOPHYSICAL RESEARCH IN SEPARATE PRESENTATIONS. VOLUME 1: ULTRASHORT WAVES [ERGEBNISSE DER BIOPHYSIKALISCHEN FORSCHUNG IN EINZELDARSTELLUNGEN. VOLUME 1: ULTRAKURZWELLEN]
B Rajewsky, ed Georg Thieme, Leipzig 1938 1 p In GERMAN

75-00044
SHORT WAVE THERAPY: THE MEDICAL USES OF ELECTRICAL HIGH FREQUENCIES
E Schliephake Actinic Press Ltd., London 1935 1 p

75-00045
RADIATION BIOLOGY, MEDICAL APPLICATIONS AND RADIATION HAZARDS
H. P Schwan 1968 1 p refs Repr. from Microwave Power Engr., v 2, 1968 p 215-234
The biological effects of microwave radiation on human tissues are reviewed Medical applications in diathermy and diagnostic instruments are described. Hazards to man, especially the eyes, of exposure to strong sources of electromagnetic radiation are discussed

75-00046
INTERACTION OF MICROWAVE AND RADIO FREQUENCY RADIATION WITH BIOLOGICAL SYSTEMS
H P Schwan 1971 2 p refs Repr from IEEE (Inst Elec Electron Eng.), Trans., v MTT-19, no 2, 1971 p 146-152
A survey of thermal and nonthermal effects of microwave and radio frequency radiation is presented with recommendations for future work Equations are presented which state dielectric constant and conductivity for tissues of high water content as functions of macromolecular content and frequency Nonthermal principles which explain many previous observations are largely

due to field-induced forces are discussed Such effects occur in the human body only at field-strength levels which are thermally dangerous. It is concluded that. (1) field-force effects cannot be enhanced by use of pulsed fields; (2) nerve membranes cannot be directly stimulated by microwave fields. (3) macromolecular resonances are not excited in body fluids and tissues A guideline for future standard work in complex fields is proposed It is based on the concept of a tolerance current density.

75-00047 Pennsylvania Univ., Philadelphia
MICROWAVE RADIATION: BIOPHYSICAL CONSIDERATIONS AND STANDARDS CRITERIA
H. P Schwan Jul 1972 1 p Repr from IEEE (Inst Elec Electron Eng). Trans Bio-Med Eng., v BME-19. Jul 1972 p 304-312
(NIH-5-R01-HE-01253)

The established physical principles relating to thermal and nonthermal effects of microwave radiation are discussed together with the effects of continuous and pulsed radiation Certain considerations indicate that present guidelines for safe exposure to microwaves are conservative There should be no need to lower the value of 10 mW/sq cm currently being used for safe long-term exposure in distance fields of antennas Approaches for extending standards to the case of complex field configurations are also discussed along with a guide number of safe tissue-current densities for the total frequency range

75-00048
HAZARDS DUE TO TOTAL BODY IRRADIATION BY RADAR
H P Schwan and K Li Nov 1956 2 p refs Repr from Proc IRE, v 44, Nov 1956 p 1572-1581

Experimental work by others at 10 cm wavelength has shown that irreversible damage to the eye is caused by electromagnetic radiation, if the energy flux is in excess of about 0 2 watt/sq cm Intolerable temperature rise, due to total body irradiation may be anticipated for flux values in excess of 0 02 watts/sq cm Hence a discussion of hazards due to total body irradiation is of primary interest This paper presents data which analyze the mode of propagation of electromagnetic radiation into the human body and resultant heat development The two quantities which are considered in detail are (1) coefficient, which characterizes the percentage of airborne electromagnetic energy as absorbed by the body, (2) distribution of heat sources in skin subcutaneous fat, and deeper situated tissues Conclusions of practical value are (1) Since sensory elements are located primarily in the skin, low-frequency radiation (f less than 1000 mc) is much more dangerous than high-frequency radiation (2) Radiation of very high frequency (f greater than 3000 mc) causes only superficial heating with much the same effects as infrared and sunlight The sensory reaction of the skin should provide adequate warning

75-00049
THE ABSORPTION OF ELECTROMAGNETIC ENERGY IN BODY TISSUES
H P Schwan and G M Piersol Dec 1954 1 p Repr from Am J Phys Med., v 33, Dec 1954 p 371-404

Effects on biological material can be placed in three categories (1) thermal, (2) specific thermal, and (3) nonthermal Volume heating is discussed as the general heating which any type of conductor or semiconductor, such as tissue, may receive under the influence of electrical currents or waves Specific thermal effects (structural heating) exist when boundaries between different types of tissues or particles can be selectively heated without substantial heating of the surrounding material Those effects which cannot be explained on a thermal basis are classified as nonthermal Energy absorption leads to the development of heat. This is defined as 'primary heat' developed in the irradiated body Primary heating produces temperature differences between various tissues and even differences within homogeneous material. The biophysicist and the physiologist work together and study actual heat distribution and associated phenomenon, such as blood flow. The clinician records the final results All three groups cooperate to obtain a complete, clear picture of the effects of radiation. The actual temperature curve, also the combined effects of primary heat development and heat flow are more important than the mechanism of absorption. A complete knowledge can be ascertained of actual temperature distributions only in animal experiments Extrapolation of this information to the human body is difficult because the amount of heat which can be absorbed by any body depends on the volume and surface of the irradiated body. Here knowledge of the fundamentals of the absorption mechanism is most helpful. It permits a prediction of how much radiant energy will be absorbed in the body; how far it penetrates; and the kind of tissue which will experience special heat development

75-00050 Bureau of Radiological Health, Rockville, Md
REGULATIONS, STANDARDS, AND GUIDES FOR MICROWAVES, ULTRAVIOLET RADIATION, AND RADIATION FROM LASERS AND TELEVISION RECEIVERS: AN ANNOTATED BIBLIOGRAPHY
L. R. Setter, D. R Snavely, D L Solem, and R. F. VanWye Apr. 1969 1 p
(Publ-999-RH-35)

The bibliography was prepared by the Standards Services Branch, Office of Criteria and Standards, in cooperation with the Electronics Products Radiation Laboratory (now the Division of Electronic Products), Bureau of Radiological Health. Copies are available for distribution to organizations and individuals who need this information. The project is a part of the Bureau of Radiological Health's program to assist organizations and individuals who are responsible for protecting the public against the harmful effects of excessive radiation. The 1967 Congressional Hearings on the control of radiation from electronic products have made clear the need to organize the information on existing regulations, standards, and guides developed by Federal, state, and municipal governments, military organizations and nongovernmental organizations This annotated bibliography was prepared in a form which aids in the comparison of existing or proposed regulations, standards, and guides for further evaluation with respect to adequacy of health protection and control, with consideration given to the economic and technologic factors

75-00051
HEARING SENSATIONS IN ELECTRIC FIELDS
H C Sommer and H E vonGierke 1964 1 p refs Repr from Aerospace Med., v 35, 1964 p 834-839

Electrophonic hearing, stimulated by an audio-frequency current passed through different types of electrode systems attached to various areas of the head and body, was previously investigated More recently, human auditory system response to modulated electromagnetic energy was reported. The experiments to be discussed in this paper were designed to study the hearing phenomena in electrostatic fields when the whole head or parts of its surface are exposed to an alternating electrostatic field of audio-frequency with and without a superimposed DC field The threshold data obtained suggest there is no other auditory stimulation excepting mechanical tissue excitation by the electrostatic forces connected with such fields Calculated threshold data for stimulation by amplitude modulated RF fields, assuming the same electromechanical excitation of normal bone and air conduction hearing, are presented and compared to the hearing phenomena in such fields reported by others Electromechanical field forces must be considered as primary causes for the hearing sensations observed with various types of electrophonic stimulations Theoretical considerations and existing experimental data make it most likely that these forces account for all reports where the hearing of pure or distorted tones (rather than indiscriminate noise) was involved. There is no evidence of any direct perception of electrical audio signals which would not go via electromechanically induced vibrations in tissue and normal reception in the cochlea. Electrostatic excitation of vibrations in tissue appears as a useful new research tool for specialized psychophysiological experimentation on the auditory or vibrotactile system.

75-00052
PATHOLOGICAL EFFECTS OF RADIO WAVES
M S. Tolgskaia and Z. V. Gordon 1973 1 p Transl. into

ENGLISH of the book "Morfoziologicheskie Izmeneniia pri Deistvii Elektromagnitnykh Voln Radiochastot" Moscow. Izdatelstvo Meditsina Press. 1971 143 p

Morphological and physiological studies of the irreversible effects of radio waves on a total of 646 rabbits, rats and mice, covering chronic and acute exposures at 500 kHz to 1 5 MHz, 14 88, 69 7, 155 and 191 MHz, lasting from several minutes to 15 months were conducted The functional and morphological changes produced by exposures of various lengths and intensities in the cariovascular and nervous systems, myocardium, reproductive organs, biochemistry, blood, eye, weight, cerebrum, cortex, spinal cord, skin and neurons are discussed Exposures in the centimeter wavelength range tended to affect the nervous fibers of the skin, internal organs and cortical neurons while exposures in the decimeter range showed no effect on the nervous activity of the skin The monograph is intended for scientists interested in the subject

75-00063
BIOLOGIC EFFECTS OF NONIONIZING RADIATION
P E Tyler, ed. 28 Feb. 1975 1 p Repr from Ann N. Y Acad. Sci., v 247, 28 Feb 1975

75-00064
QUANTIFYING HAZARDOUS ELECTROMAGNETIC FIELDS: SCIENTIFIC BASIS AND PRACTICAL CONSIDERATIONS
P F Wacker and R R Bowman 1971 1 p refs Repr. from IEEE (Inst Elec. Electron. Eng.). Trans., v MTT-19, no. 2, 1971 p 178-187

The complications and problems of quantifying hazardous EM fields involving source-subject coupling, reactive near-field components, multipath components, and arbitrary polarization are examined General discussion of dosimetric measurements and hazard survey measurements is given, and also some basic considerations for the design of field probes for these measurements Recommendations are given for suitable parameters for quantifying complicated EM fields, and essential and desirable characteristics for hazard survey meters are stated Several recently designed hazard survey probes are capable of measuring these recommended parameters in many complicated fields of interest, and improved instruments are anticipated

75-00065
BIOLOGIC EFFECTS STUDIES ON MICROWAVE RADIATION TIME AND POWER THRESHOLDS FOR PRODUCTION OF LENS OPACITIES BY 12.3 cm MICROWAVES
D B Williams, J P Monahan, W J. Nicholson, and J J Aldrich 1955 2 p refs Repr from Amer Med Ass Arch Ophthalmo., v 54, 1955 p 863-874

Opacities can be produced in the eyes of anesthetized rabbits by single exposures to 12 3 cm microwaves Time and power requirements for experimental opacity formation ranges between 5 minutes, at 0 59 watt/sq cm., and 90 minutes, at 0 29 watt/sq cm The power densities of this threshold correspond to a thermal flux of 8 4 to 4 1 cal/sq cm/min The trend of the threshold beyond 90 minutes is bracketed between 0 22 and 0 12 watt/sq cm for 4 5 hours of sustained irradiation The failure of the protracted period of exposure at 0 12 watt/sq cm to cause any discernible effect suggests the proximity of a power density below which opacity production by this method is not practical. As nearly as can be determined by ophthalmoscopic examination, all opacities are formed in the posterior lens segment and in some respects resemble lesions produced by certain ionizing irradiations The quantity of 12 3 cm radiation reflected and transmitted by the eye is unknown, but sufficient energy is absorbed to produce temperatures of 49 to 53 C at the site of the lens which later becomes cataractous A latent period of 1 to 14 days elapses before the onset of discernible opacities The lesions, in order of increasing severity, are classified according to appearance as minimal, circumscribed, and diffuse Minimal lesions may not be detrimental to sight, but the last two types interfere with vision Other ocular effects are observed but, for the most part, appear less significant than lens injury Secondary effects are not consistently related to the development of lens damage except in some cases of the diffuse lesion, where severe and persisting periorbital edema appears to be a precursor of cataract formation.

Section 2.

MICROWAVES: General References

75-00056
EFFECT OF MICROWAVES ON THE REACTIONS OF THE WHITE BLOOD CELLS SYSTEM
S Baranski 1972 1 p Repr from Acta Physiologica Polonica, v 23, 1972 p 685-695

75-00057
EFFECT OF CHRONIC MICROWAVE IRRADIATION ON THE BLOOD FORMING SYSTEM OF GUINEA PIGS AND RABBITS
S Baranski 1971 1 p Repr from Aerospace Med, v 42, 1971 p 1196 1199

One hundred guinea pigs and 100 rabbits were irradiated in an anechoic room with continuous or pulsed microwaves in the 10 cm wave band at 3 5 mW/cm power density for 3 months, 3 hrs daily Peripheral blood bone marrow, lymph nodes and spleen were examined Increases in absolute lymphocyte counts in peripheral blood abnormalities in nuclear structure and mitosis in the erythroblastic cell series in the bone marrow and in lymphoid cells in lymph nodes and spleen were observed These changes are a cumulative result of repeated irradiations The underlying mechanism seems difficult to explain in terms of thermal effects Extrathermal complex interactions seem to be more probable

75-00058
ELECTROENCEPHALOGRAPHICAL AND MORPHOLOGICAL INVESTIGATION UPON THE INFLUENCE OF MICROWAVES ON THE CENTRAL NERVOUS SYSTEM
S Baranski and Z Edelwesn 1967 1 p Repr from Acta Physiol Pol (Poland), no 18, 1967 p 517-532

75-00059
MICROWAVE EFFECTS ON MITOSIS IN VIVO AND AND IN VITRO
S Baranski, P Czerski, and S Szmigielski 1969 1 p Repr from Genetica Polonica, v 10 1969 p 3 4

75-00060
INVESTIGATIONS OF THE BEHAVIOR OF CORPUSCULAR BLOOD CONSTITUENTS IN PERSONS EXPOSED TO MICROWAVES
S Baranski and P Czerski 1966 1 p Repr from Lek Wojsk v 42, 1966 p 903 909

75-00061 California Univ, Los Angeles
EFFECTS OF MODULATED VERY HIGH FREQUENCY FIELDS ON SPECIFIC BRAIN RHYTHMS IN CATS
S M Bawin, R J Gavalas Medici, and W R Adey 1973 1 p Repr from Brain Res (Amsterdam), v 58, no 2, 1973 p 365 384

The effects of exposures to low intensity less than 1 mW/sq cm), very high frequency (VHF) (147MHz) electrical fields, amplitude modulated [AM] at biological frequencies (1 25 Hz), were studied on untrained and conditioned chronically implanted cats The fields were applied between 2 Al plates (identical voltages, 180 deg phase shift) firmly anchored to the floor of an isolation booth, especially designed for use of VHF fields The animals were restrained in a hammock, the longitudinal axis of the body kept parallel to the field plates EEG and EOG [electro oculograms] were recorded through a system of low pass filters on a Model 6 Grass EEG and an Ampex FR 1100 tape recorder, behavior was continuously observed through a closed circuit TV A series of animals was operantly trained to produce specific transient brain rhythms following periodic (every 30 s) presentations of a light flash stimulus The levels of performance were established (visual and spectral analysis) during conditioning and extinction schedules for a series of cats submitted to VHF fields AM at the dominant frequencies of the selected transient patterns and for a control group, in the absence of fields The irradiated animals differed markedly from the control group in the rate of performance, accuracy (in terms of frequency bandwidth) of the reinforced patterns and resistance to extinction (minimum of 50 days vs 10 days) The specificity of the frequency of the modulation was tested on another group of untrained animals where spontaneous transient patterns were used to trigger for short epochs (20 s following every burst) the VHF fields AM at various frequencies The fields were acting as reinforcers (increasing the rate of occurrence of the spontaneous rhythms) only when modulated at frequencies close to the biologically dominant frequency of the selected intrinsic EEG rhythmic episodes Interaction routes between external fields and CNS are discussed Perhaps AM VHF fields influence neuronal membrane excitability

75-00062
THE EFFECT OF 10-CENTIMETER AND ULTRASHORT WAVES ON THE REPRODUCTIVE FUNCTION OF FEMALE MICE
A N Bereznitskaya 1968 1 p Repr from Gig Tr i Prof Zabolev (USSR), no 9, 1968 p 33-37

C[illegible] irradiation of female mice with 10 cm waves of 10 m[illegible] intensity was found to bring about certain changes in the course of estrus cycle finding their expression in an increased duration of normal cycle at the expense of prolonged diestrus and metaestrus stages A partial sterility of irradiated females was observed The progeny of female mice irradiated prior to conception, and especially before and during gestation proved to be defective with instances of stillbirth and a considerable proportion of postnatal lethality The offsprings of irradiated females showed retarded weight and body size gain as against controls and developed at a slower rate

75-00063 IIT Research Inst, Chicago, Ill
SUSCEPTIBILITY OF CARDIAC PACEMAKERS TO ELF MAGNETIC FIELDS (METHOD AND CRITERION FOR EVALUATING ELF MAGNETIC FIELD INTERFERENCE EFFECTS ON CARDIAC PACEMAKER FUNCTION)
J E Bridges, E E Brueschke, M P Kaye, D A Miller, and C D Port Apr 1971 1 p
(Contract N00039-71-C-0111)
(AD 737237, IITRI-E6185 1)

In the report it was concluded that the extremely low fequency (ELF) magnetic field levels which interfere with the operation or cardiac pacemakers are much greater than those expected from a conceptual defense SANGUINE communication system This conclusion was based on an experimental program in which the effect of extremely low frequency (10-100 Hz) magnetic fields on cardiac pacemakers was studied. Objectives of the program were to determine a safe level (threshold) for a magnetic field in this frequency range and to establish a method and criterion for evaluating the interference effects Examples of electromagnetic fields affecting implanted heart pacemakers are presented

75-00064
BIOLOGICAL EFFECTS OF MICROWAVE AND RADIO FREQUENCY RADIATION
S F Cleary Jun 1970 1 p refs Repr from Critical Rev Environ Control, v 1, Jun 1970 p 257-306

A comprehensive up-to-date survey of all aspects of the interaction of microwaves and r f with biological systems is presented Mechanisms of interactions are given, together with

detailed reviews of specific effects such as thermal, lenticular, testicular and genetic damage. A section is devoted to the measurements of power levels and to standard for human exposure.

75-00065
CONSIDERATIONS ON THE EVALUATION OF THE BIOLOGICAL EFFECTS OF EXPOSURE TO MICROWAVE RADIATION
S F Cleary Feb 1970 1 p refs Repr from Am Ind Hyg Assoc J v 31 no 1, Jan Feb 1970 p 52 59
A review is given of the thermal (less than 10 mW/sq cm) and non thermal effects of microwave and ultrahigh frequency radiation exposure on organisms, organs, cells bacteria and biological molecules. A discussion of permissible exposure limits based on existing experience, and of the relevant difficulties is presented

75-00066
UNCERTAINTIES IN THE EVALUATION OF THE BIOLOGICAL EFFECTS OF MICROWAVE AND RADIOFREQUENCY RADIATION
S F Cleary Oct 1973 1 p Repr from Health Phys, v 25 Oct 1973 p 387 404

75-00067
ANALYSIS OF OCCUPATIONAL EXPOSURE TO MICROWAVE RADIATION
P Czerski and M Siekierzynski Plenum, N Y 1975 1 p Presented in Fundamental and Applied Aspects of Nonionizing Radiations Proceedings of the 7th Rochester Intern Conf on Environ Toxicity R chester, N Y 5 7 Jun 1974

75-00068
HEALTH SURVEILLANCE OF PERSONNEL OCCUPATIONALLY EXPOSED TO MICROWAVES. 1. THEORETICAL CONSIDERATIONS AND PRACTICAL ASPECTS
P Czerski M Siekierzynski and A Gidynski 1974 1 p Repr from Aerospace Med, v 45 no 10, 1974 p 1137 1142
Principles of health surveillance of microwave workers are presented. An analysis of the incidence of disorders considered contraindications for occupational microwave exposure among 841 males aged 20 to 45 years and exposed occupationally to microwaves for various periods was made. The analyzed population was subdivided into two groups differing only in respect to microwave exposure low i e below 0 2 mW/sq cm and high i e between 0 2 mW sq cm and 6 mW/sq cm. No dependence of the incidence of disorders considered contraindications for occupational microwave exposure on the exposure level or duration of occupational exposure could be demonstrated. The authors feel that similar studies carried out on groups exposed at other power density levels are needed

75-00069
A CLINICAL STUDY OF THE RESULTS OF EXPOSURE OF LABORATORY PERSONNEL TO RADAR AND HIGH FREQUENCY RADIO
L E Daily 1943 1 p Repr from US Navy Med Bull v 41, 1943 p 1052 1065
A group of 45 men with exposure to radar and high frequency radio varying from 2 months to 9 years were observed for 12 months. Periodic physical and blood examinations of these individuals were within the normal range. The reproductive tissues did not seem to have suffered clinically any demonstrable damage as judged by the number of conceptions and normal pregnancies during the time of exposure of the fathers to radar. No abnormal or premature alopecias that could be connected with exposure to radar were found. There have been no unusual dermatological manifestations. It was concluded that During the preliminary and present work on radar and high frequency radio by personnel who are constantly exposed to the equipment and its emanations both in a shielded and an unshielded condition, there has been no clinical evidence of damage to these personnel. It is thought advisable that directives as to shielding of equipment and periodic med[illegible] checkup of personnel be continued to prevent a rather remote possibility of an occasional injury due to overexposure of personnel. It is to be noted that the radio frequency energy of radar is not different from that of other high frequency radio or diathermy units of an equivalent average power

75-00070
EVALUATION OF THYROID FUNCTION IN PERSONS OCCUPATIONALLY EXPOSED TO MICROWAVE RADIATION
R Denisiewicz, R Dziuk, and M Siekierzynski 1970 1 p Repr from Polskie Archiwum Medycyny Wewnetrznej (Poland), no 45, 1970 p 19

75-00071
ACTION OF ULTRAHIGH FREQUENCY RADIATION (WAVELENGTH 21 cm) ON TEMPERATURE OF SMALL LABORATORY ANIMALS
L DeSeguin and G Castelain 1947 1 p Repr from Compt Rend Acad Sci (Paris), v 224, 1947 p 1662

75-00072
AUTONOMIC AND CARDIOVASCULAR DISORDERS DURING CHRONIC EXPOSURE TO SUPER-HIGH FREQUENCY ELECTROMAGNETIC FIELDS
E A Drogichina, N M Konchalovskaya, K V Glotova, M. N Sadchikova, and G V Snegova 1966 1 p Repr from Gig Tr i Prof Zabolev (USSR), v 10, 1966 p 13-17

75-00073
EXPERIMENTAL RESEARCH ON THE BIOLOGICAL EFFECTS OF 12-CENTIMETER LOW-INTENSITY WAVES
Yu D Dumansky, A M Serdyuk, L I Litvinova, L A Tomashevskaya, and V M Popovich 1972 1 p Repr from Health in inhabited localities, edition 2 (Kiev), 1972 p 29-31

75-00074
CHANGES IN THYROID FUNCTION WITH CHRONIC EXPOSURE TO MICROWAVE RADIATION
N A Dyachenko 1970 1 p Repr from Gig Tr Prof Zabol (USSR), no 14, 1970 p 51-52
A thyroid study using L 131 was performed in humans systematically exposed to microwaves in the 1 cm range. Duration of exposure was 3 5 hours per week. The amount of absorbed L 131 was determined 2, 4, and 24 hours after ingestion using gamma ray intensity measurement near the isthmus; basal metabolism was also determined. Numerical studies show that microwave radiation impairs the correlations of nervous processes and diencephalic regulation in organs and tissues

75-00075
IMPACT OF SHF ELECTROMAGNETIC RADIATION ON THE FUNCTIONAL STATE OF THE MYOCARDIUM
N A Dyachenko 1970 1 p Repr from Voen Med Zhurn (USSR), no 2, 1970 p 35 37

75-00076
FIELD MEASUREMENT OF ULTRAVIOLET, INFRARED, AND MICROWAVE ENERGIES
J H Fanney, Jr and C H Powell Aug 1967 1 p refs Repr from Am Ind Hyg Assoc J, v 28, no 4, Jul Aug 1967 p 335 342
The industrial hygienist has for some time been aware of the possible hazards which exist from the energies in the non ionizing portion of the electromagnetic spectrum. Potential sources of these radiations and instrumentation available for field measurement are reviewed. The instruments by categorical types, their advantages, disadvantages, and specificity for various portions of the spectrum, as well as the interpretation of their responses are discussed. The article contains recommendations for avoiding gross errors in field surveys

75-00077
OCCUPATIONAL HYGIENE PROBLEMS IN WORKING WITH ULTRASHORT-WAVE TRANSMITTERS USED IN TV AND RADIO BROADCASTING
N N Goncharova, V B Karamyshev and N V Maksimenko

1966 1 p Repr from Gig Tr i Prof Zabolev (USSR), v 1C 1966 p 10 13

The aim of the research was to study the health aspects of the working conditions of personnel employed in the vicinity of ultrashort wave television transmitters, and to determine the effects of the electromagnetic fields within these wavelengths The studies were conducted at radio and television stations whose basic equipment consisted of 2 5 kw transmitters operating at 67 230 Mc The 16 transmitters studied each consisted of a metal cabinet housing, enclosing power tubes condensers, oscillators power line and switching components and control and measuring component·

75-00078 Academy of Sciences (USSR), Moscow
OCCUPATIONAL HEALTH ASPECTS OF RADIO-FREQUENCY ELECTROMAGNETIC RADIATION
Z V Gordon 1970 1 p Repr from Ergonomics and Phys Environ Factors, Occupational Safety and Health Ser 21 (GENEVA) 1970 p 159 174

The biological effects of electromagnetic radiation depends on their frequency band (or wavelength) intensity and exposure time The typical effect for biological action of radio frequency radiation is presented by a thermal effect which can produce fever or a local increase of temperature in some organs and tissues determined by dielectric loss factor The dielectric loss of energy in tissues increases as the frequency is increased and it leads to a more effective transformation of electromagnetic field energy to thermal energy The thermal effects of radio frequency radiation depends on its intensity and wave length The clinical picture of thermal effects is accompanied by typical morphological alternations characteristic for hyperthermal A thermal effect of sufficient deviation involves modifications of a degenerative type in the cells of parenchymatose organs and myocarde dystrophic processes in the synapses and the cells of different sectors of central nervous system and autonomic nervous system Irradiation with smaller doses without increase of body temperature is not however indifferent for the organism The central nervous system is the most inhibited The organism reaction of radio frequency radiation consists of two phases stimulative and inhibitive Repeated irradiations of low intensity provoke a permanent functional alteration as a result of cumulative biological effects This should be considered in establishing regulations for radiation exposure Exposure to radio frequency radiation may result in functional troubles of the nervous and the cardiovascular systems shown by hypothonia bradycardia modification in cardiac conductivity etc and alterations of endocrinal humoral processes In general workers exposed to radio frequency radiation of different frequencies show a common basic alteration of the central nervous and cardiovascular system where only the degree of these alterations vary In persons exposed to the action of microwaves (ultrahigh frequencies), the alterations are more pronounced Furthermore initial morphological alterations of eye lens can be observed The alterations in persons working with sources of high frequency occur much more rarely and are less pronounced The stimulation of biological acticity is directly proportional to the shortening of wavelength This phenomenon is determined by biophysical processes and the absorption mechanism of energy of different wavelengths by organic heterogenic tissues The experimental data obtained in the Institute of Occupational Hygiene and Disease of Academy of Medical Sciences provide evidence on the above effects

75-00079
THE PROBLEM OF THE BIOLOGICAL ACTION OF UHF
Z V Gordon 1960 1 p Repr from Trudy Nii Gigyena Truda i Profzabol v 1, 1960 p 5 7

75-00080
SOME DATA ON THE EFFECT OF CENTIMETER WAVES (EXPERIMENTAL STUDIES)
Z V Gordon, Ye A Lobanova, and M S Tolgskaya 1955 1 p Repr from Gig Sanit (USSR), no 12, 1955 p 16 18

75-00081 Joint Publications Research Service, Arlington, Va
THE EFFECT OF CENTIMETER RADIO WAVES ON MOUSE FERTILITY
S F Gorodetskaya 1963 1 p Transl into ENGLISH from Fiziol Zh SSSR (Moscow) v 9, 1963 p 394-395 (JPRS 21200)

Studies of the development of the offspring and histological changes in sex organs of irradiated female white mice (irradiated with radio waves of 3 cm, at a frequency of 577 c/s, an average power of 34 5 kw, for 5 minutes) mated with unirradiated male mice indicated the following (1) overall irradiation with centimeter waves has a strong effect on the sex glands of female mice, (2) there is a sharp drop in the fertility of irradiated mice, as evidenced by the reduced litter sizes and a higher stillbirth rate, and (3) changes were noted in the morphology and functioning of the sex organs of mice upon irradiation with centimeter waves

75-00082
ELECTROMAGNETIC FIELDS AND RELATIVE HEATING PATTERNS DUE TO A RECTANGULAR APERTURE SOURCE IN DIRECT CONTACT WITH BILAYERED BIOLOGICAL TISSUE
A W Guy Feb 1971 1 p refs Repr from IEEE Trans, v MTT 19, no 2, Feb 1971 p 214 223

Expressions were derived and evaluated for the electromagnetic fields and associated relative heating patterns in two layered biological tissue media exposed to a direct contact rectangular aperture source The source consisted of a linearly polarized electric field distribution specified in the plane of the aperture The results may be used for many biomedical applications ranging from the design of diathermy to the establishment of standardized electromagnetic field intensities in connection with research on electromagnetic effects in living biological media

75-00083
A NOTE ON EMP SAFETY HAZARDS
A W Guy 1974 1 p Repr from IEEE Trans Biomed Eng, 1974

75-00084
MICROWAVE INDUCED ACOUSTIC EFFECTS IN MAMMALIAN AUDITORY SYSTEMS AND PHYSICAL MATERIALS
A W Guy, C K Chou, J C Lin, and D Christensen Feb 1974 1 p Presented at New York Acad of Sci Conf on Biol Effects of Nonionizing Radiation, Feb 1974 Submitted for publication

75-00085
THERAPEUTIC APPLICATIONS OF ELECTROMAGNETIC POWER
A W Guy J F Lehmann, and J B Stonebridge Jan 1974 1 p Repr from Proc IEEE, v 62, no 1, Jan 1974 p 55-75

75-00086
ELECTROPHYSIOLOGICAL EFFECTS OF ELECTROMAGNETIC FIELDS ON ANIMALS
A W Guy, J C Lin, and C K Chou Jun 1974 1 p Presented at Rochester Environ Toxicity Conf, Rochester, N Y, Jun 1974

75-00087 Medical Biological Lab RVO-TNO, The Hague (Netherlands)
BIOLOGICAL EFFECTS OF MICROWAVE RADIATION, PART 1
H Heering and P M M Vanosch Nov 1971 1 p (MBL 1971 7 Pt-1)

The only biological effects of microwave radiation that until now could be proved experimentally with certainty were purely thermal in nature the heating and sometimes subsequent damaging of biological material due to absorption of high intensity microwaves Although not completely explained by theory, the mechanism of thermal effects of microwave exposure appears to be reasonably well understood. In practice the effects due to overheating can be prevented rather easily.

78-00078
BILATERAL LENTICULAR OPACITIES OCCURRING IN A TECHNICIAN OPERATING A MICROWAVE GENERATOR
F G Hirsch and J T Parker 1952 1 p Repr from Arch Ind Hyg Occup Med. v 6. 1952 p 512-517

A case study of the damage done to the eyes of an adult male upon exposure to microwave radiation is reviewed Since microwave energy has been used as a modality of physical therapy for a number of years without any record of ocular damage, this case study was published to recall to the attention of ophthalmologist. industrial physicians and microwave workers the potentialities of microwave radiation. in order that the use of this form of energy will be accompanied by appropriate respect and precautions

78-00079
CHANGES OF PHAGOCYTIC ACTIVITY AND MOBILITY OF NEUTROPHILS UNDER THE INFLUENCE OF MICROWAVE FIELDS
A I Ivanov Kirov Order of Lenin Mil Med Acad. Leningrad 1962 1 p

78-00080 Service de Sante des Armees. Toulon (France)
BIOLOGICAL EFFECTS OF UHF ELECTROMAGNETIC RADIATION
R Joly and B Servantie Mar 1972 1 p

Very high fruquency radiation effects. emitted by radar equipment. on the human organism were investigated The physiological and physiopathological aspects are outlined Data also cover pulse duration. penetrative power. energy density. and exposure time

78-00081
CHANGES IN THE ELECTRICAL ACTIVITY OF THE RABBIT CEREBRAL CORTEX DURING EXPOSURE TO A UHF-HF ELECTROMAGNETIC FIELD. PART 2: THE DIRECT ACTION OF THE UHF-HF FIELD ON THE CENTRAL NERVOUS SYSTEM
Yu A Kholodov 1963 1 p Repr from Biul Eksp Biol Med (USSR) no 56 1963 p 42-46

The effect of an UHF field on the EEG after injury to the telereceptors. alone or concurrent with an incision of the mesencephalon at the inferior colliculi. was studied in rabbits The animals' reactions after single deafferentation. or combined with the brain section. were the same as in the normal controls. that is. the EEG showed an increase in amplitude and a decrease in frequency The effect was evaluated in terms of response frequency and latent period The same reaction. even more pronounced was noted in the islated brain. which suggested that the telereceptors are not primarily concerned with the perception of the UHF field Incision at the mesencephalic level increased the duration of the response but shortened the latent period The diencephalon and telecephalon located above the incision were capable of responding to the UHF field The mean latent period was increased after deafferentation However. tce distribution curve in different individuals showed two maxima No morphological explanation could be found to account for the difference in response However. the cortex and the hypothalamus showed distinct histological changes

78-00082
THE EFFECT OF AN ELECTROMAGNETIC FIELD ON THE CENTRAL NERVOUS SYSTEM
Yu A Kholodov 1962 1 p Repr from Priroda (USSR) no 4. 1962 p 104-105

The effects of a static magnetic field on the central nervous system were studied in birds. fish. and mammals by the conditioned reflex method Reactions to light. sound and electric current were utilized The field strength varied from 1 to 800 Oe and exposure time from seconds to hours Although food seeking and electrodefensive reflexes to a magnetic field could be established. it was easier in fish to develop inhibitory conditioned reflexes In this aspect magnetism proved a greater stimulus than light or sound In pigeons. alimentary conditioned reflexes were inhibited in 70% of the cases by the magnetic field In fish the strength of the electric current needed to stimulate a fish to quiver increased by 45% in a field of 100 to 200 Oe In rabbits it was shown that the forebrain and diencephalon, when deprived of nerve connections to the receptors, react more to a magnetic field than an intact brain It is concluded that a magnetic field acts as (1) a weak stimulus, (2) is usually inhibitory, and (3) acts directly on the forebrain and diencephalon

78-00083
THE EFFECT OF CENTIMETER WAVES OF DIFFERENT INTENSITIES ON THE BLOOD AND HEMOPOIETIC ORGANS OF WHITE RATS
I A Kitsovskaya 1964 1 p Repr from Gig Tr i Prof. Zabolev (USSR), v 8. 1964 p 14-20

Reported are the effects of the administration of a dose of radiation with 10-centimeter wave pulses upon the blood and hemopoietic organs (bone marrow and spleen) in white rats After establishing each rat's background level for hemoglobin content. the number of erythrocytes, reticulocytes, and leukocytes and their differential, radiation of the animals was begun with the microwave intensity and exposure periods varied for each group Periodic blood studies were performed, and changes in the number of formed blood elements in each animal were compared and the results recorded

78-00084
POTENTIAL RADIATION HAZARD IN RADAR INSTALLATIONS
H J Koerner 1967 1 p Repr from Zent Arbeitsmed Arbeitsschutz. v 17. 1967 p 1-5

78-00085
THE OCULAR EFFECTS OF MICROWAVES ON HYPOTHERMIC RABBITS: A STUDY OF MICROWAVE CATARACTOGENIC MECHANISMS
P O Kramar, A F Emery, A W Guy, and J C Lin Feb 1974 1 p Presented at the New York Acad of Sci Conf on Biol Effects of Nonionizing Radiation. Feb 1974

78-00086
ACCURACY LIMITATION IN MEASUREMENTS OF HF FIELD INTENSITIES FOR PROTECTION AGAINST RADIATION HAZARDS
H R Kucia Nov 1972 1 p Repr from IEEE (Inst Elec Electron Engr). Trans Instr Meas. v IM 21. Nov 1972 p 412-415 Presented at the IEEE and Intern Union of Radio Sci Conf on Precision Electromagnetic Meas. 13th. Boulder. Colo. 26-29 Jun 1972

78-00087 Methodist Hospital. Houston. Tex
A MICROWAVE DECOUPLED BRAIN-TEMPERATURE TRANSDUCER
L E Larsen, R A Moore, and J Acevedo Apr 1974 1 p Repr from IEEE (Inst Elec Electron Engr). Trans Microwave Theory Tech. v MTT-22. Apr 1974 p 438-444 Prepared in cooperation with Westinghouse Elec Corp. Baltimore

The measurement of brain temperature during moderate to high level exposure to microwave radiation was considered Bench test studies of conventional temperature transducers in microwave environments have demonstrated artifacts responsible for errors of several degrees centigrade These findings led to a program for the development of systematic test procedures and the design of electrodes with artifact reduced to 0 1 C.

78-00088
TEMPERATURE DISTRIBUTIONS IN THE HUMAN THIGH, PRODUCED BY INFRARED, HOT PACK IN MICROWAVE APPLICATIONS
J F Lehmann, D R Silverman, B A Baum, N L Kirk, and V C Johnston 1966 1 p refs Repr from Arch Phys Med Rehabil. v 47. 1966 p 291-299

In this study it was found that during luminous heat, infrared, and hot pack application. blood flow changes occurred in the skin and subcutaneous tissues which cooled the superficial tissue

layers As a result, the temperatures in the superficial tissue layers dropped in spite of the continuous application of the modalities This temperature drop occurred after an initial exposure of approximately 10 minutes In spite of this cooling effect resulting from an increase in blood flow the superficial tissue layers were not cooled enough to allow a therapeutically effective rise in the temperature of deep tissues such as musculature None of the modalities investigated proved to be effective as a deep heating agent There was no significant difference in the temperature distributions irrespective of the technique of application or the type of superficial heating modality used A statistically significant difference in temperature distributions produced by the superficial heating modalities and by microwaves (2456 mc and 900 mc) was found From the therapeutic point of view, microwaves operating at 2456 mc were not so effective in heating musculature as were microwaves operating at the frequency of 900 mc

76-00099
EFFECT OF MICROWAVES ON CARDIAC RHYTHM OF RABBITS DURING LOCAL IRRADIATION OF BODY AREAS
N A Levitina 1964 1 p Repr from Byull Eksperim Biol i Med, v 58, 1964 p 67 69

76-00100
POWER DEPOSITION IN A SPHERICAL MODEL OF MAN EXPOSED TO 1-20-MHz ELECTROMAGNETIC FIELDS
J C Lin, A W Guy (Washington Univ Seattle), and C C Johnson (Utah Univ Salt Lake City) Dec 1973 1 p Repr from IEEE Trans Microwave Theory and Tech v MTT 21 Dec 1973 p 791 797 Presented at IEEE Intern Microwave Symp Boulder Colo 4-6 Jun 1973
(Contract F41609 73-C 0002 Grant GM 16436)
(HEW 16 P 5616/0 11)

76-00101 Washington Univ Seattle Dept of Rehabil Med
MICROWAVE SELECTIVE BRAIN HEATING
James C Lin, Arthur W Guy and George H Kraft 1974 1 p Repr from J Microwave Power v 8 no 3-4 1973 p 275 286

Microwave induced heating patterns in mammalian brains were studied using spherical models through theory and experiment Differential absorption by various portions of the brain produced local hyperthermia Though microwave heating is extremely rapid the precise temperature rise depends on the intensity of incident radiation and the duration of exposure Preliminary animal (cat) experiments indicate that a temperature of 43 C is attained in 90 s without tissue damage, suggesting the possibility [illegible] microwa[illegible]ferential hyperthermia as an adjunct [illegible] therapy [illegible] brain cancer

76-00102
THE EFFECT OF ELECTROMAGNETIC FIELDS ON THE BIOELECTRIC ACTIVITY OF CEREBRAL CORTEX IN RABBITS
M N Livanov A B Tsypin, Yu G Grigoryev, V G Krushchev, S M Stepanov, and V M Ananyev 1960 1 p Repr from Biul Eksp Biol Med (USSR), no 49 1960 p 63 67

76-00103
THE EFFECT OF RADIO-FREQUENCY ELECTROMAGNETIC FIELDS IN THE 191 AND 155 [illegible] RANGE ON THE CONDITIONED REFLEXES OF ANIMALS
Ye A Lobanova and A V [illegible]anarova 1968 1 p Repr from Gig Tr Prof Zabol (USSR), no 3, 1968 p 76-80

76-00104
CHANGES IN CONDITIONED-REFLEX ACTIVITY OF ANIMALS DUE TO EXPOSURE TO MICROWAVES OF VARIOUS FREQUENCY RANGES
Ye A Lobanova 1964 1 p Repr from Gig Tr AMN SSSR (USSR), no 2, 1964 p 13-19

76-00105
CHANGE IN HIGHER NERVOUS ACTIVITY AND INTERNEURON CONNECTIONS IN THE CEREBRAL CORTEX OF ANIMALS UNDER THE INFLUENCE OF UHF
Ye A Lobanova and M S Tolgskaya 1960 1 p Repr from Tr Gig Tr Prof AMN SSSR (USSR), no 1, 1960 p 69-74

76-00106
BIOLOGICAL EFFECTS OF RF ELECTROMAGNETIC WAVES
K Marha 1963 1 p Repr from Pracovni Lekarstvi, Prague 15 (Czechoslovakia), 1963 p 387 393

76-00107
NEUROPHYSIOLOGICAL EFFECT OF 3-cm MICROWAVE RADIATION
R D McAfee 1961 1 p refs Repr from Am J Physiol, v 200 no 2 1961 p 192 194

Neurophysiological effects from locally applied 3-cm microwave irradiation were demonstrated on decerebrate and anesthetized cats and shown to be the result of thermal stimulation of peripheral sensory nerve fibers The penetrating characteristic of 3 cm radiation heats these fibers within the skin and subcutaneous tissue to 45 + or - 2 C at which temperature a nociceptive response was elicited from the experimental animals The irradiation was applied to small areas of skin or short sections of nerve trunks rich in sensory fibers and the nociceptive response obtained was quite different from the signs of a hyperthermal state seen during whole-body microwave irradiation

76-00108
THRESHOLDS FOR LENTICULAR DAMAGE IN THE RABBIT EYE DUE TO SINGLE EXPOSURE TO CW MICROWAVE RADIATION: AN ANALYSIS OF THE EXPERIMENTAL INFORMATION AT A FREQUENCY OF 2.45 GHz
Donald J McRee Dec 1971 1 p Repr from Health Phys (N Ireland) v 21 Dec 1971 p 763 769

This work presents a review of the literature as regards to the power and time thresholds for opacity formation in the eye due to continuous microwave radiation Temperature measurements in the vitreous humor were used to develop an analytical model (using basic principles and experimentally determined rate constants) which predicts the power and time thresholds for a frequency of 2 45 GHz Although this model was not extended to other frequencies, it provides a context in which a general analytical model can be developed when more temperature data become available Two empirical equations were derived which predict the power and time thresholds as a function of frequency

76-00109
EFFECTS OF EXPOSURE TO MICROWAVES: PROBLEMS AND PERSPECTIVES
S M Michaelson 1974 1 p Repr from Environ Health Perspectives, 8 p 133 156

76-00110
STANDARDS FOR PROTECTION OF PERSONNEL AGAINST NON-IONIZING RADIATION
S M Michaelson 1974 1 p Repr from Am Indust Hyg Ass J, 35 p 766 784

76-00111 Rochester Univ., N.Y. Dept of Radiation Biology and Biophysics
RELEVANCY OF EXPERIMENTAL STUDIES OF MICROWAVE INDUCED CATARACTS TO MAN
S M Michaelson 1972 1 p Sponsored by AEC
(UR 3490-103)

An extensive literature review is presented of studies which have attempted to assess the relationship of exposure to microwaves and the subsequent development of cataracts The studies include numerous investigations in animals and several surveys among human populations On the basis of these studies the following conclusions are made (1) The estimated exposure levels with which clinically significant cataracts have

been associated have generally been quite high and well above 100 mW/sq cm (2) In general the studies are only qualitative and do not give any relation between the actual power level and pathology (3) The individuals studied in the surveys could have been exposed to ionizing radiation just as well as microwaves (4) The health hazard posed by the possibility of microwave induced cataract formation would appear minor because the power densities required for opacification are seven to eight times the maximum permissible exposure levels suggested for human exposure (10 mW/sq cm)

75-00112 Rochester Univ N Y Dept of Radiation Biology and Biophysics

THERMAL EFFECTS OF SINGLE AND REPEATED EXPOSURES TO MICROWAVES

S M Michaelson Oct 1973 1 p Presented at the Intern Symp on Biol Effects and Health Hazards of Microwave Radiation Warsaw 15 Oct 1973

(UR 3490 317 Conf 731042 1)

Thermal effects of single and repeated exposure to microwaves with respect to threshold phenomena and physiological adaptation are reported Threshold response was noted in rabbits exposed to 2 45 5 40 8 23 and 10 05 GHz microwaves localized to the eye at power density time durations sufficient to result in opacities Adaptive reactions were noted in the dog rabbit and rat For example repeated whole body exposure of dogs to 2 88 GHz and 1285 MHz pulsed microwaves at power densities from 20 to 165 mW/sq cm 1 to 6 hours per day for 2 to 4 weeks showed thermal adaptation or acclimatization as reflected by diminished temperature response as the exposures continued Rats repeatedly exposed to 2 45 GHz pulsed reveal adaptive reaction of functional changes Acetylcholine levels in the blood of rabbits and functional changes such as arterial pressure alterations in rabbits also shows the phenomenon of adaptation as a result of repeated exposures to thermogenic levels of microwaves The use of these studies as a means of examining some fundamental aspects of thermoregulation acclimatization or adaptation and interrelated cardiovascular biochemical and neuroendocrine functions is suggested

75-00113

THE INFLUENCE OF MICROWAVES ON IONIZING RADIATION EXPOSURE

S M Michaelson, R A E Thomson L T Odland, and J W Howland Feb 1963 1 p refs Repr from Aerospace Med v 34 Feb 1963 p 111 115

The effectiveness or practicality of microwave exposure as a method for enhancement of recovery and/or protection against radiation can only be inferred from the data presented The results suggest that additional work should be done to evaluate the potential of this procedure in counteracting or minimizing the effects of ionizing radiation Various time intensity factors of ionizing radiation frequency power level pulse height and width interrelationships for microwave irradiation as well as intervals between exposures of these two energies should be considered in such investigations 2800 MHz, PW (prf 360, pulse width 2 microseconds), 100 165 mW/sq cm, dogs. MW + X ray (250kV, 2 R/min) Results are reported from studies in dogs on the effect of microwave exposure on response to ionizing radiation Irradiation with 25000 R resulted in death within 24 hr in 2 of 10 dogs with a previous history of microwave exposure Nine of 10 normal irradiated dogs died in the same period Neurological manifestations were less severe in the microwave treated dogs The results suggest that the possibility of using microwave treatment to counteract or minimize the effects of ionizing radiation should be explored

75-00114

EFFECTS OF ELECTROMAGNETIC RADIATIONS ON PHYSIOLOGIC RESPONSES

S M Michaelson, R A E Thomson, and W J Quinlan Mar 1967 1 p refs Repr from Aerospace Med, v 38, Mar 1967 p 293 298

Studies were performed on dogs exposed to 1240 Mc/sec pulsed microwaves, at a field intensity of 50 mW/sq cm, six hours per day for five consecutive days Some dogs with additional exposures were included For comparison dogs previously irradiated with 1000 kVp X rays (50 R/min) either to the wholebody (300 R) upper body (1900 R) or lower body (900 R) were exposed to microwaves in a similar manner Alterations in cardiopulmonary thyroid and erythropoietic function of normal dogs and greater sensitivity of X irradiated dogs to microwaves are noted In general, these studies indicate that repeated exposure to 1240 Mc/sec microwaves at 50 mW/sq cm, can produce functional changes in the dog which if extrapolated to man would be indicative of homeostatic insufficiency and decrement in performance capability even though overt incapacitation may not take place Whether thermal nonthermal, or both of these are the contributing factors in the response to microwave exposure, there are sufficient experimental and human survey evidence to indicate that microwave exposure results in alterations in compensatory and homeokinetic mechanisms of the body The effect of microwave exposure at 50 mW/sq cm in the normal animal should alert us to the caution that has to be exerted when any consideration is given to raising the presently accepted maximum permissible exposure of 10 mW/sq cm

75-00115

ENDOCRINE REACTIONS AND CHANGES IN ENDOCRINE GLANDS UNDER INFLUENCE OF MICROWAVES

H Mikolajczyk 1972 1 p Repr from Med Lotnicza (Poland), no 39, 1972 p 39 51

On the base of modern concept of endocrine system, the effect of microwaves on hormonal reactions and changes in endocrine glands is discussed There exists a marked thermic effect of microwaves on the endocrine system, while still lack valid observations concerning occurrence of hormonal changes under influence of nonthermic doses of microwaves The symptoms of slight thyroid hypofunction were shown, probably these symptoms are due to dysfunction of the hypophysis Changes in cholinesterase activity in fluids and tissues were also observed Damaging effect of microwave irradiation on gonads was also proved, probably the primary place of action in this case seems to be the hypothalamus hypophysis system

75-00116

SURVIVAL PERIODS OF NORMAL AND HYDROPHYSECTOMIZED RATS EXPOSED TO ACUTE MICROWAVE IRRADIATION

H Mikolajczyk 1973 1 p Repr from Patol Polska (Warsaw), v 24, 1973 p 325 332

Normal (37), hypophysectomized (18) and partially hypophysectomized (16) rats were exposed to lethal doses of microwave radiation (2860 MHz, 120 mW/sq cm) Period of survival (t prime) was measured in minutes (+ or 1/2 minute) It was found that the survival period (t prime) in normal rats was largely a function of body mass (m) The regression equations for t prime m, t prime m 2/3 power and t prime m 3/4 power were of comparable values with linear or close to linear course There were no significant differences between means of absolute survival periods between normal rats hypophysectomized or partially hypophysectomized rats Survival period per unit of body weight (t prime/10 X m, t prime X m 2/3rds power and t prime X 10 3/4th power) was significantly longer in hypophysectomized rats than in partially hypophysectomized and/or normal rats Correlations between t prime m, t prime m 2/3rds power, and t prime m 3/4th power were positive and highly significant in normal rats There were no such correlations in hypophysectomized rats The results indicate that hypophysectomy diminished the sensitivity of rats to acute effects of microwaves It also seems that thermal effect of microwaves depends not only on the size of body surface and of body mass, but also on general metabolic rate in tissues

75-00117 Rochester Univ N Y Dept of Radiation Biology and Biophysics

BIOLOGICAL EFFECTS OF MICROWAVE RADIATION

William C Milroy and Sol M Michaelson Jun 1970 1 p Repr from Health Phys (N Ireland), v 20, Jun 1971 p 567 575

Concern over the possible hazards of exposure to microwave radiation has lately been on the increase. Increasing industrial and commercial use of microwave generators for heating and cooking, increasing power of radar sets, and expansion of the broadcasting industry have resulted in more widespread interest in the possible biological effects of these electromagnetic radiations. A critical review of the literature on biological effects of microwave irradiation is presented along with an analysis of the present status of standards and hazard evaluation.

75-00118 Rochester Univ., N.Y.
MICROWAVE CATARACTOGENESIS: A CRITICAL REVIEW OF THE LITERATURE
W. C. Milroy and S. M. Michaelson. Jan 1972. 1 p. Repr. from Aerospace Med., v. 43, Jan 1972, p. 67-75

Concern with the possible hazards of exposure to microwave radiation has recently been on the rise. Legislation to protect the public from hazardous exposure to microwaves has been enacted and even stricter controls have been proposed. The lens of the eye has been considered one of the most sensitive organs to microwave radiation. A review of the Western and Soviet bloc literature on microwave cataractogenesis is presented as well as an analysis of the value of this literature in terms of standard setting and hazard evaluation.

75-00119
STUDIES OF VISCERAL LESIONS OBSERVED IN MICE AND RATS EXPOSED TO UHF WAVES. A PARTICULAR STUDY OF THE EFFECTS OF THESE WAVES ON THE REPRODUCTION OF THESE ANIMALS
L. Miro, R. Loubiere, and A. Pfister. 1965. 1 p. Repr. from Rev. Med. Aeronaut. (Paris), v. 4, 1965, p. 37-39

Rats were exposed to ultrashort waves (10 cm waves of 3105 MHz - or - 15 MHz frequency) for 190, 300, and 450 hours. The animals suffered no ill effects of general anatomy nor of physiology when there was a means of eliminating the heat formed in the body from the electromagnetic transformation of energy. The specific effects of ultrashort waves on gonad structure and reproductive function were investigated in mice and rats. The waves had no adverse effect on either gonad structure or reproductive function.

75-00120
HEAT STRESS DUE TO RF RADIATION
William Walden Mumford. Nov 1969. 1 p. Repr. from Proc. IEEE, v. 57, no. 2, Feb 1969, p. 171-178

The radiation protection guide (RPG) number of 10 mW/sq cm is generally accepted for normal environmental conditions. For conditions of moderate to severe heat stress, the guide number should be appropriately reduced. A proposal to reduce the guide number one mW/sq cm for every temperature humidity-index (THI) point above 70 (until 1 mW/sq cm is reached) is examined in terms of heat stress.

75-00121
OBSERVATIONS ON MICROWAVE HAZARDS TO USAF PERSONNEL
L. T. Odland. Jul 1972. 1 p. Repr. from J. Occup. Med., v. 14, Jul 1972, p. 544-547

Microwave injury experiences and possible potential hazards of microwave exposures to microwave operators are considered in an attempt to assess the validity of present USAF exposure safety limits. Particular attention is given to the incidence of cataract in members of USAF personnel exposed to microwave radiation. It is pointed out that the present 10 mW/sq cm exposure limit may be subject to a future revision when warranted by new evidence. It is also indicated that the eye is not the most vulnerable organ and that the use of cataract development as a criterion of microwave damage is conditional.

75-00122
CLINICAL ASPECTS OF MENTAL DISORDERS FOLLOWING EXPOSURE TO SUPER-HIGH FREQUENCY ELECTROMAGNETIC WAVES
T. N. Orlova. 1971. 1 p. Presented in Cerebral Mechanisms of Mental Illness (Kazan), p. 16-18

75-00123 Raytheon Co., Waltham, Mass.
COMPARISON OF POTENTIAL DEVICE INTERFERENCE AND BIOLOGICAL EXPOSURE HAZARDS IN MICROWAVE LEAKAGE FIELDS
J. M. Osepchuk. 1971. 1 p. Repr. from Intern. Electromagnetic Compatibility Symp. Record, 1971, p. 156-161. Presented at the Intern. Electromagnetic Compatibility Symp., Philadelphia, 13-15 Jul 1971

The potential for interference in devices including medical devices and instrumentation exposed to leakage or stray fields of microwave sources is explored. A study of semiconductor devices in arbitrary circuitry suggests a maximum potential interference in microwave fields. Experimental data on interference of demand pacemakers in microwave fields is reviewed in the context of electromagnetic compatibility. Potential interference levels are far below biological exposure hazard levels. Effective methods of reducing susceptibility of devices to microwave radiation are shown to include shielding and filtering techniques.

75-00124
OCCUPATIONAL HYGIENE AND THE EFFECT OF RADIO-FREQUENCY ELECTROMAGNETIC FIELDS ON WORKERS
Yu. A. Osipov. Meditsina Press, Leningrad. 1965. 1 p.

75-00125
THE EFFECT OF VHF-HF UNDER INDUSTRIAL CONDITIONS
Yu. A. Osipov. 1952. 1 p. Repr. from Gig. Sanit. (USSR), no. 6, 1952, p. 22-23

75-00126
EFFECT OF RADIATION OF THE ORDER OF CM AND M WAVES ON HUMANS HEALTH
J. Pazderova. Dec 1968. 1 p. Repr. from Prac. Lek. (Czechoslovakia), v. 20, Dec 1968, p. 447-457

The biological hazard contributed by microwave irradiation is evaluated and the pathological effects of microwaves on personnel working within close range of electrostatic fields are discussed. Tissue destruction, morphological effects on the central nervous system, and general effects of intensive microwave irradiation on living organisms during chronic exposure are reviewed. A critical evaluation of maximum permissible levels of microwave radiation exposure is given.

75-00127
THE HEALTH CONDITION IN WORKERS EXPOSED FOR A LONG PERIOD TO THE ELECTROMAGNETIC RADIATION IN THE ULTRA SHORT WAVE FREQUENCY BAND (30-300 MHz)
Jana Pazderova, Vera Bryndova, Jan John, Edgar Lukas, Marcela Nemcova, and Jan Zubnk. 1971. 1 p. Repr. from Prac. Lek. (Czechoslovakia), v. 23, no. 6, 1971, p. 265-271

Altogether 58 television transmitting station employees, 49 men and 9 women, were examined. The mean age was 32.1 years and the mean period of employment 7.2 years. The frequency band of the transmitters was 48.5-230 MHz, the mean intensity of the electromagnetic field 2.9 V/m, SD 0.4 and range 0-9.2. The mean value of irradiation for 1 working day, i.e., the sum of the field intensity in V/m and period of irradiation expressed in hr was 30.7, SD 3.8 and range 6.5-97.1. The error in the measurement methods is stated 30%. The health condition was assessed on the basis of case history and the results of the following examinations: ECG, X-ray of the heart and lungs, BSR (blood sedimentation rate), urine analysis, liver tests, BWR (body weight ratio) and gynecological examination of women. Examinations compared and statistically evaluated with the control groups were blood pressure, blood picture, including thrombocytes, protein spectrum, glycemic curve, ophthalmologic examination, neurologic, psychiatric and psychologic examinations. No signs of damage by electromagnetic radiation were found. In the laboratory results, the mean values of plasma proteins were significantly increased. Although this phenomenon is not considered pathologic, its connection with electromagnetic

radiation exposure can not be excluded. The results of the other examinations did not differ form the control groups.

76-00128 Missouri Univ. Columbia. Environmental Health Center.
HEALTH SURVEILLANCE OF MICROWAVE HAZARDS
Charles H. Powell and Vernon E. Rose 1970 1 p Repr from Amer Ind Hyg Ass J v 31 no 1 1970 p 358-367

Since the early 1940's industrial use of electronic equipment that emits electromagnetic energy in the microwave region has increased. Concurrent with this growth is the development of data on the biological effects of this form of radiant energy and the establishment of exposure criteria. Various local, state, and federal health programs and survey techniques and instrumentation are reviewed. Standardization of survey techniques is suggested and recommendations are presented regarding future activities in establishments where persons may be potentially exposed to microwaves from ovens and other commercial and industrial sources of energy.

76-00129
THE EFFECT OF MICROWAVES ON LIVING ORGANISMS AND BIOLOGICAL STRUCTURES
A. S. Presman 1965 1 p Repr from Usp. Fiz. Nauk (USSR) no 86 1965 p 263-302

Review of those microwave biology experiments that are considered to be of particular interest to physicists, described so as to be intelligible to nonbiologists. The absorption of microwaves by the tissues of living organisms is considered under two aspects: energy losses due to ion conductivity and dielectric losses due to polarization relaxation in water molecules. The dosimetry of microwaves for the evaluation of their effects on humans and animals is discussed. The reactions of human organisms to low-intensity microwaves and the reactions of animal organisms to microwaves of all intensities are considered. The changes caused by microwaves in animal tissues and organisms are discussed. The cellular and molecular effects of electromagnetic radiation of all wavelengths are considered.

76-00130
NONTHERMAL ACTION OF MICROWAVES ON THE HEART RATE OF ANIMALS. 1: ACTION OF CONTINUOUS MICROWAVES
A. S. Presman and N. A. Levitina 1962 1 p Repr from Byull Eksperim Biol i Med no 1 1962 p 41-44

76-00131
NONTHERMAL ACTION OF MICROWAVES ON THE HEART RATE OF ANIMALS. 2: ACTION OF PULSED MICROWAVES
A. S. Presman and N. A. Levitina 1962 1 p Repr from Byull Eksperim Biol i Med no 2 1952 p 39-42

76-00132 School of Aerospace Medicine, Brooks AFB, Tex.
POSSIBLE CATARACTOGENIC EFFECTS OF RADIOFREQUENCY RADIATION
D. R. Reader, D. L. Epstein, and J. H. Kirk Aug 1971 1 p (AD-730922; SAM-Review-3-71; SAM-TR-71-24)

Use of the electromagnetic spectrum for man's benefit has increased tremendously. However, the complete understanding of its potential and real biologic hazards has failed to keep pace. The present threshold limit value for microwaves is the subject of much debate. The eye and lens were damaged by microwaves experimentally, but the mechanism of damage is as yet unexplained. A preliminary study was performed using radio frequency exposure and rhesus monkeys. No cataracts were formed at a frequency of 19.27 MHz. Problems involved in future radio frequency studies, and areas which require further studies are discussed.

76-00133
PROTECTION OF PERSONNEL EXPOSED TO RADAR MICROWAVES
F. Sacchitelli and G. Sacchitelli 1960 1 p Repr from Folia Med (Naples) v 43 1960 p 1219-1229

76-00134
CLINICAL PICTURE OF THE CHRONIC EFFECTS OF ELECTROMAGNETIC MICROWAVES
N. M. Sadchikova and A. A. Orlova 1958 1 p Repr from Indust Hyg Occupat Dis (USSR) v 2 1958 p 16-22

76-00135
THE TIME CONSTANTS OF PEARL-CHAIN FORMATION
M. Saito and H. P. Schwan 1961 1 p refs Repr from the Proc. of the Fourth Tri-Service Conf on Biol Effects of Microwave Radiation 1961 p 85-97 Presented at the 4th Tri-Service Conf on Biol Effects of Microwave Radiation

As the results of the investigations made on the transient behavior of the pearl chain formation, it is concluded that: (1) The time constants involved in the pearl chain formation are of the order of a second for the radius of 1 micron, and they are proportional to the cube of the radius. (2) The time constants are not strongly dependent on the field intensity when it is small, and they are inversely proportional to the square of the field intensity when it is large. (3) For particles of several microns or of larger sizes, the time constants become as large as hundreds of seconds. (4) The pulsed applied field is as effective as is expected from its r.m.s. value for usual radar systems. (5) The hazards due to heat become pronounced before the field intensity is large enough for the pearl chain to form if the particle size is less than 10 microns.

76-00136
ALTERNATING-CURRENT FIELD INDUCED FORCES AND THEIR BIOLOGICAL IMPLICATIONS
H. P. Schwan and L. D. Sher 1969 1 p refs Repr from J. Electrochem. Soc. V 116 1969 p 170

Steady state field induced forces on particles of microscopic size become significant at field strength values of the order of 100 v/cm. They include pearl chain formation, i.e. the alignment of particles in the direction of the imposed field, and the orientation of nonspherical particles. The time constant, which describes the speed of these phenomena depends on field strength, and particle and other parameters. For pulsed fields, a lower level of applied average power can suffice to evoke the phenomena mentioned. Biological implications include the possibility of nonthermal effects of biological significance.

76-00137
INDUCED FIELDS AND HEATING WITHIN A CRANIAL STRUCTURE IRRADIATED BY AN ELECTROMAGNETIC PLANE WAVE
A. R. Shapiro, R. F. Lutomirski, and H. T. Yura 1971 1 p refs Repr from IEEE Transactions, v MTT-19, no 2, 1971 p 187-196

The induced fields and the static heating patterns within a multilayered spherical model that approximates the primate cranial structure are calculated. The model was heated by plane waves in the microwave spectrum. The relation of the model to the biological structure and the sensitivity of the results to the uncertainties in the dimensions and electrical properties of biological material are investigated. A method of solution for both the scattered and the interior fields for a sphere with an arbitrary number of electrically different concentric layers is developed in a form readily amenable to machine computation. It is shown that the semi-infinite slab model is inappropriate for calculating the microwave radiation dosage for the human head and similar structures.

76-00138
HEALTH SURVEILLANCE OF PERSONNEL OCCUPATIONALLY EXPOSED TO MICROWAVES. 3: LENS TRANSLUCENCY
M. Siekierzynski, P. Czerski, A. Gidynski, S. Zydecki, C. Czarnecki, E. Dziuk, and W. Jedrzejczak 1974 1 p Repr from Aerospace Med. v 45 no 10 1974 p 1146-1148

The incidence of lenticular opacities was examined in 841 microwave workers with histories of various periods of occupational exposure at 2 W/sq m to 60 W/sq m (507 individuals) or at below 2 W/sq m (334 individuals). The incidence of lenticular opacities was compared between both

groups, analyzed within each group, and subdivided according to age or duration of occupational exposure. It was found that lenticular opacities are not dependent on the exposure level, duration time, nor is there a significant correlation with age.

76-00139
HEALTH SURVEILLANCE OF PERSONNEL OCCUPATIONALLY EXPOSED TO MICROWAVES. 2: FUNCTIONAL DISTURBANCES
M Siekierzynski, P Czerski, H Milczarek, A Gidynski, C Czarnecki, E Dziuk, and W Jedrzejczak 1974 1 p Repr from Aerospace Med., v 45 no 10, 1974 p 1143-1148

The incidence of functional disturbances (neurotic syndrome, gastro-intestinal tract disturbances, cardio-circulatory disturbances with abnormal ECG) was analyzed in 841 males aged 20 to 45 years, occupationally exposed to microwaves for various periods of time. The whole population was subdivided into two groups differing only in respect to microwaves exposure-low, i.e. below 0.2 mW/sq cm and high, i.e. between 0.2 mW/sq cm and 6 mW/sq cm. No dependence of the incidence of functional disturbances on the exposure level or duration of occupational exposure (years) could be demonstrated.

76-00140
CATARACT OF BOTH EYES WHICH DEVELOPED AS A RESULT OF REPEATED SHORT EXPOSURES TO AN ELECTROMAGNETIC FIELD OF HIGH DENSITY
I S Shimkovich and V G Shilyayev 1959 1 p Repr from Vestnik Oftalmologii (Moscow) 72 p 12-16

76-00141 Bureau of Radiological Health, Rockville, Md.
NERVOUS AND BEHAVIORAL EFFECTS OF MICROWAVE RADIATION IN HUMANS
Charlotte Silverman 1973 1 p Repr from Am J Epidemiol v 97, no 4, 1973 p 219-224

The health implications or hazards of exposure to non-ionizing microwave radiation must be known to develop protective standards and guides, on a firm, biologic basis. A review is made of exposed workers with respect to findings of a neurologic or behavioral character. Clinical studies (9) of groups employed in the operation, testing, maintenance and manufacture of a wide variety of microwave-generating equipment in Czechoslovakia, Poland, the U.S.A. and the U.S.S.R. are presented. The symptoms and signs commonly described in the Soviet and other studies include headache, increased fatigability, increased irritability, dizziness, loss of appetite, sleepiness, sweating, difficulties in concentration or memory, depression, emotional instability, dermographism, thyroid gland enlargement, and tremor of extended fingers. They are regarded as typical microwave-induced functional disturbances of the CNS and are called the neurasthenic or asthenic syndrome. The frequency and severity of clinical signs increase with long-term exposure. The clinical syndromes, but not necessarily the EEG changes, are generally reversible with temporary (or permanent) removal from work and with symptomatic and general supportive treatment.

76-00142
CHANGES IN RESPIRATION, PULSE RATE AND GENERAL BLOOD PRESSURE DURING IRRADIATION OF ANIMALS WITH SHF-UHF
A G Subbota 1957 1 p Repr from Tr Voyenno Med Akad i Kirov (USSR), v 73, 1957 p 111-115

76-00143
THE EFFECT OF PULSED SHF-UHF ELECTROMAGNETIC FIELDS ON THE HIGHER NERVOUS ACTIVITY OF DOGS
A G Subbota 1958 1 p Repr from Byul Eksp Biol Med (USSR), no 46, 1958 p 55-61

76-00144
A REVIEW OF INTERNATIONAL MICROWAVE EXPOSURE GUIDES
J R Swanson, V E Rose, and C H Powell Oct 1970 1 p refs Repr from Am Ind Hyg Ass J., v 31 no 5, Sep-Oct 1970 p 623-629

The use of higher frequency microwave generating equipment has increased considerably since the development of radar and range finder equipment in the early 1940's. Occupational exposure criteria were not officially proposed in the United States until 1953 when a maximum exposure of 10 milliwatts per square centimeter was established for United States Air Force operations. Since then, many organizations have proposed or adopted criteria which have expanded on the concept of a single exposure limit to incorporate other factors involved in a biological response. A review of representative exposure criteria used in the United States is presented along with those adopted in other countries such as England, Russia, and Poland, and others. Where criteria differ from United States guidelines, a short review of the scientific evidence is provided.

76-00145
STUDIES ON THE EFFECT OF RADIO FREQUENCY WAVES ON BIOLOGICAL MACROMOLECULES
S Takashima 1966 1 p refs Repr from IEEE Trans Bio-Med Eng., BME-12, 1966 p 28-31

The effect of radio-frequency electric fields on various biologic materials was examined. Particularly, the effects on alcohol dehydrogenase and DNA were carefully investigated. To avoid the effects of heating, a pulsed electric field was used, and samples were also rigorously cooled. The activity of alcohol dehydrogenase and the structure of DNA were not altered, however, even by the prolonged irradiation at high-field intensity between 1 and about 60 Mc/s.

76-00146 Environmental Protection Agency, Rockville, Md. Twinbrook Research Lab.
MICROWAVE ENERGY ABSORPTION IN TISSUE
R A Tell Feb 1972 1 p
(PB 208233)

A guide to several dosimetric techniques used to study energy absorption in biological tissues is presented. A detailed account is given of the calculational concepts, gathered from the literature, which are used to determine the degree of power absorption within such tissue systems as well as the spatial distribution of this absorbed dose as heat and consequently, the tissue temperature elevations which may be experienced in the model. Both a graphic analytic technique using the Smith chart and a mathematical derivation of the appropriate computing formulas are given. Adequate derivation of the appropriate computing formulas are given.

76-00147
MODIFICATION OF X-IRRADIATION LETHALITY IN MICE BY MICROWAVES (RADAR)
R A E Thomson, S M Michaelson, and V W Howland Apr 1965 1 p refs Repr from Radiation Res., no 24, Apr 1965 p 631-635

Pretreatment of mice with microwave alters the lethal response to X radiation. Mean survival time of microwave-treated animals given ionizing radiation is longer than that for animals not subjected to microwaves. Alteration of response to ionizing readiation injury by microwave treatment has now been observed in three species of experimental animals-dogs, rats and mice. Microwave exposure (whole body) was of three types (2800 MHz, pulsed wave, 100 mW/sq cm) (1) single exposure of 10 minutes radiation, (2) daily exposures of 10 min for a total of 14 days, and (3) continued exposure until approximately 30% of the animals being exposed died. Total X-irradiation (250 kV) administered was 700, 800 of 900 R.

76-00148
MICROWAVE RADIATION AND ITS EFFECT ON RESPONSE TO X-RADIATION
R A E Thomson, S M Michaelson, and J W Howland Mar 1967 1 p refs Repr from Aerospace Med., no 38, Mar 1967 p 252-255

Dogs were exposed to simultaneous microwave (2800 Mcycles/sec, 100 mW/sq cm) and X-ray (250 KVP,

16(' R 4 6 R/min) exposure, or to the same X ray exposure nine months after a total of 90 hours of multiple microwave exposure Mortality was greater in animals treated with microwaves and was most marked following simultaneous microwave and X irradiation Deaths were hemopoietic in nature Survival appeared best in dogs showing minimal leucocyte and neutrophil changes immediately after X irradiation Hematocrit erythrocyte sedimentation rate reticulocyte rectal temperature, body weight food and water consumption changes are presented Microwave treatment can modify the response to X irradiation and its effect appears related to the total microwave exposure duration of microwave exposure rectal temperature response, time interval before X irradiation, total X irradiation and X ray dose rate Modification of ionizing radiation injury at the hematopoietic level is indicated

76-00149
MORPHOLOGICAL CHANGES IN EXPERIMENTAL ANIMALS UNDER THE INFLUENCE OF PULSED AND CONTINUOUS WAVE SHF-UHF RADIATION
M S Tolgskaya, Z V Gordon, and Ye A Lobanova 1960 1 p Repr from Tr Gig Tr Prof AMN SSSR (USSR), no 1, 1960 p 90 98

76-00150
CHANGE IN THE NEUROSECRETORY FUNCTION OF THE HYPOTHALAMUS AND THE NEURO-PITUITARY BODY DURING CHRONIC IRRADIATION WITH CENTIMETER WAVES OF LOW INTENSITY
M S Tolskaya and Z V Gordon 1968 1 p Presented in The Biological Effect of Radio Frequency Fields Works of the Lab of Radio-Frequency Electromagnetic Fields, Inst of Work Hygiene and Occupational Diseases, AMN SSSR Moscow p 87 97

76-00151
CHANGE IN THE BLOOD OF ANIMALS SUBJECTED TO A SHF-UHF FIELD
N V Tyagin 1957 1 p Repr from Voyenno Med Akad Kirov (Leningrad) v 73 1957 p 116 126

76-00152
ELECTROCARDIOGRAM CHANGES IN DOGS AFFECTED BY SHF-UHF ELECTROMAGNETIC FIELDS
N V Tyagin 1957 1 p Repr from Voyenno Med Akad Kirov (USSR), v 73, 1957 p 84-101

76-00153
EFFECT OF HIGH-FREQUENCY ELECTROMAGNETIC FIELD UPON HAEMOPOIETIC STEM CELLS IN MICE
D R A Vacek 1972 1 p Repr from Folia Biologica (Prague), v 18, 1972 p 292 297

76-00154 Naval Medical Research Inst Bethesda, Md
EXAMINATION OF THE CORNEA, FOLLOWING EXPOSURE TO MICROWAVE RADIATION
R J Williams and E D Finch Apr 1974 1 p Repr from Aerospace Med, v 45 Apr 1974 p 393-396

This study was designed to detect alterations in the corneas of rabbits caused by multiple exposure to either 2450 MHz continuous wave or 2860 MHz pulsed radiation at an average power field density of 225 mW/sq cm Hematoxylin and eosin stained sections of corneas were examined In some cases, the pattern of tritiated thymidine uptake into corneal cells was evaluated by autoradiography Radiation did not appear to influence the normal cornea or the healing process in the wounded cornea

76-00155
ON THE QUESTION OF CONDITIONED CARDIAC REFLEXES, THE FUNCTIONAL AND MORPHOLOGICAL STATE OF CORTICAL NEURONS UNDER THE EFFECT OF SUPERHIGH-FREQUENCY ELECTROMAGNETIC FIELDS
M I Yakovleva T P Shiyafer, and I P Tsvetkova 1968 1 p Repr from Zh Vysshei Nervoi Deyatelnosti (USSR), no 18, 1968 p 973 978

76-00156 Armed Forces Radiobiology Research Inst, Bethesda, Md
GAMMA-AMINOBUTYRIC ACID METABOLISM IN RATS FOLLOWING MICROWAVE EXPOSURE
G H Zeman, R L Chaput, Z R Glazer, and L C Gershman 1974 1 p Repr from J Microwave Power v 8, no 3/4, 1973 p 213 216

The metabolism of the inhibitory neurotransmitter aminobutyric acid (GABA), was studied in rats chronically exposed to 2 86 GHz microwaves at an incident power level of 10 mW/sq cm or acutely exposed to incident power levels of 40 or 80 mW/sq cm No changes occurred in whole brain GABA levels or in the activity of the enzyme which synthesizes GABA, L-glutamate decarboxylase, following these exposures Results indicate that brain GABA metabolism was not affected by exposure to microwave radiation

Section 3.

ULTRASOUND: Documents of Major Importance

76-00157
THE EFFECTS OF INDUSTRIAL AIRBORNE ULTRASOUND ON HUMANS
W I Acton 1974 1 p Repr from Ultrasonics (England), v 12, 1974 p 124-128

Reported physiological effects resulting from the exposure of small animals to ultrasound cannot be transposed directly to man. There is no evidence of permanent biological changes, including hearing loss as a result of normal industrial exposures to pure ultrasound, although some effects may occur as a result of experimental laboratory exposures. The high levels of high frequency audible sound which accompany many industrial processes, particularly those producing cavitation, may cause unpleasant subjective effects, including headaches, nausea, tinnitus, and possibly fatigue in persons without hearing loss at these frequencies.

76-00158
ULTRASONIC TECHNIQUES IN BIOLOGY AND MEDICINE
Basil Brown, ed and D Gordon, ed 1967 1 p
(LC-68-3830)

76-00159
ULTRASONIC ABSORPTION AND REFLECTION BY LUNG TISSUE
F Dunn and W J Fry 1961 1 p Repr from Phys med Biol (England), v 5, 1961 p 401

The acoustic reflection and absorption coefficients of both normal and diseased (Pneumonitis) excised lung tissue (dog) were experimentally determined at a frequency of 0.98 Mc/sec. It was found that the physiological saline-lung interface reflects 50% of the sound energy falling on it at normal incidence. The acoustic amplitude absorption coefficient per unit path length of lung tissue is 4.7/cm. The very high absorption exhibited can be explained as caused by radiation of acoustic energy by the pulsating gaseous structures in the lung tissue. The theory indicates that the absorption coefficient of lung tissue should approach a minimum as the frequency is increased above 1 Mc/sec and should then increase at still higher frequencies. The diseased lung exhibited an acoustic absorption coefficient approximately 25% less than that of normal lung specimens.

76-00160
ULTRASONIC THRESHOLD DOSAGES FOR THE MAMMALIAN CENTRAL NERVOUS SYSTEM
F Dunn and F J Fry Jul 1971 1 p Repr from IEEE (Inst Elec Electron Eng), Trans Bio-Med Eng, v 18, Jul 1971 p 253-256

76-00161
ULTRASOUND: ANALYSIS AND EXPERIMENTAL METHODS IN BIOLOGICAL RESEARCH
W J Fry and F Dunn 1962 1 p Repr from Phys Tech in Biol Res, v 4 p 261-394

76-00162
THE POSSIBILITY OF HAZARD IN MEDICAL AND INDUSTRIAL APPLICATIONS OF ULTRASOUND
C R Hill 1968 1 p Repr from Brit J Radiol (England), v 41, 1968 p 561-569

76-00163
BIOLOGICAL EFFECTS OF ULTRASOUND
C R Hill 1972 1 p Repr from Ultrasonics in Clinical Diagnosis, ch 9, 1972 p 165-176

76-00164
SAFETY OF ULTRASOUND IN DIAGNOSIS
C R Hill 1974 1 p Presented at Toxicity Meeting, Rochester, 1974

76-00165
ACTION OF ULTRASOUND ON ISOLATED CELLS AND CELL CULTURES
C R Hill [1974] 1 p

76-00166 Rochester Univ, N Y Dept of Electrical Engineering
FREQUENCY DEPENDENCE OF THRESHOLDS FOR ULTRASONIC PRODUCTION OF THERMAL LESIONS IN TISSUE
R M Lerner, E L Carstensen, and F Dunn 1973 1 p Repr from J Acoust Soc Am, v 52, no 2, 1973 p 504-506

The ultrasonic intensity threshold for producing lesions in mammalian brain tissue is not a strong function of frequency (over the range of 1-10 MHz) for exposures longer than 1 s. A model is presented to explain this apparent lack of frequency dependence. It is assumed that the maximum temperature developed in the lesion volume for a given pulse duration is determined by the absorption coefficient of that tissue and the distribution of the acoustic intensity over the treated volume (sharpness of the beam). The former is observed experimentally to be nearly linearly dependent upon frequency in the range 1-10 MHz and the latter, for a good lens, is related inversely to frequency. Temperature calculations are presented which account for heat loss (by diffusion), the frequency dependence for the beam geometry and the absorption coefficient. These lead to nearly frequency independent curves for threshold dosages beyond 1-s exposure, suggesting that thermal processes may be predominant for such exposures.

76-00167 National Bureau of Standards, Boulder, Colo Electromagnetics Div.
BIBLIOGRAPHY OF DIAGNOSTIC AND THERAPEUTIC APPLICATIONS OF ULTRASOUND
Robert F Metzker, comp Sep 1972 1 p
(NBS-10-738-Pt-2)

This bibliography on the diagnostic and therapeutic applications of ultrasound is one of a series on ultrasound. It was prepared as a report of the information collected to date and on file at the Electromagnetics Division of the National Bureau of Standards. Ultrasound refers to ultrasonic energy and phenomena with critical frequency components in the range of 0.5 to 50 MHz. The documents cited were collected for review during a study of the need for a system of national reference standards for ultrasound.

76-00168
ACOUSTIC STREAMING
W L Nyborg 1965 1 p Repr from Phys Acoustics, v 2B p 265-331

76-00169 Bureau of Radiological Health, Rockville, Md
INTERACTION OF ULTRASOUND AND BIOLOGICAL TISSUES: WORKSHOP PROCEEDINGS
J M Reid, ed and M R Sikov, ed Sep 1972 1 p Proc. Held at Seattle, 8-11 Nov. 1971 Sponsored by Battelle Memorial Inst., NSF, FDA, PHS, and HEW
(DHEW/FAA-73-8008, BRH/DBE-73-1)

Ultrasound generating devices have become increasingly prevalent and diverse in recent years. Their use is expected to continue to grow, particularly in diagnostic and therapeutic applications. Although there has been an awareness of the range of biological effects that can result from exposure to ultrasound, there is a paucity of information that can be used to assess the risk of man's exposure to this form of energy. This workshop was held to provide an indication of the present state of knowledge

in the area of ultrasound bioeffects and to define areas in which further work needs to be done

75-00170 Guys Hospital Medical School, London (England)
A STUDY OF THE PRODUCTION OF HEMORRHAGIC INJURY AND PARAPLEGIA IN RAT SPINAL CORD BY PULSED ULTRASOUND OF LOW MEGAHERTZ FREQUENCIES IN THE CONTEXT OF THE SAFETY FOR CLINICAL USAGE
K J W Taylor and J B Pond 1972 1 p Repr from Brit J Radiol (England), v 45, no 533, 1972 p 343-353

The spinal cords of adult rats were irradiated with ultrasound using peak intensities of 25 or 50 V/sq cm at frequencies of 0 5 to 6 MHz Delivery of energy was pulsed to avoid thermal effects In most experiments, 10 msec pulses were separated by intervals of 100 msec Such treatment resulted in paraplegia and or gross hemorrhage into the cord The appearance of hemorrhage was a more consistent occurrence and was used to compare the effects of ultrasound of varying parameters Damaging ability was maximal at the lowest frequency employed (0 5 MHz): it decreased with increasing frequency to 5 MHz, at which frequency neither paraplegia nor hemorrhage could be produced The same method was used to investigate the effects of hypoxia when it was found that an arterial partial pressure of O2 of 50 mm rendered the tissue more vulnerable to ultrasonic damage by a factor of 40% The effects of changing the duty cycle were similarly investigated Hemorrhage occurred whenever an accumulated dose-time was received which time was characteristic of each frequency and independent of the changed time-averaged intensity resulting from the changed duty cycle

75-00171
PHYSICAL PRINCIPLES OF ULTRASONIC DIAGNOSIS
P N T Wells 1969 1 p

75-00172
ULTRASONICS IN CLINICAL DIAGNOSIS
P N T Wells, ed 1972 1 p

Section 4.

ULTRASOUND: General References

75-00173
A CRITERION FOR THE PREDICTION OF AUDITORY AND SUBJECTIVE EFFECTS DUE TO AIR-BORNE NOISE FROM ULTRASONIC SOURCES
W. I. Action 1968 1 p Repr from Ann. Occup. Hyg. (England), v 11, no. 3 p 227-234

75-00174 Copenhagen Univ. (Denmark).
DIAGNOSTIC ULTRASOUND USED AS AN ALTERNATIVE FOR X-RAY EXAMINATION IN PREGNANCY. EXPERIMENTAL WORK ABOUT POSSIBLE TERATOGENIC EFFECTS OF DIAGNOSTIC ULTRASOUND
Jens Bang 1971 1 p In DANISH Presented at 3d Nordic Radiation Protection Conf., Copenhagen, Denmark, 18 Aug 1971
(Conf-710847)

During the last 10 to 12 yrs. application of ultrasonics for diagnostic purposes in medicine has increased especially in obstetrics. In order to obtain qualitative and quantitative evaluation it was found reasonable to investigate the teratogenic effects, if any, of ultrasound with frequences equalling those applied for diagnostic purposes in comprehensive animal experiments. An investigation including a little more than 6500 fetuses of mice exposed to ultrasound of high effect was carried out Both continuous and pulsed 2.25 MHz ultrasound were used in the experiment.

75-00175
CHROMOSOME BREAKAGE AND ULTRASOUND
E Boyd, U. Abdulla, I Donald, J E E Flemming, A. J. Hall, and M A Ferguson-Smith 1971 1 p Repr from Brit. Med J. (England), v. 2, 1971 p 501-502

75-00176
BIOLOGICAL ACTION OF ULTRASOUND IN RELATION TO THE CELL CYCLE
P R Clarke and C. R. Hill 1969 1 p Repr from Exp. Cell Res., v 58 p 443-444

75-00177
PHYSICAL AND CHEMICAL ASPECTS OF ULTRASONIC DISRUPTION OF CELLS
P. R Clarke and C R. Hill 1970 1 p Repr. from J Acoust. Soc Amer., v. 47 p 649-653

75-00178
SYNERGISM BETWEEN ULTRASOUND AND X-RAYS IN TUMOUR THERAPY
P R Clarke, C. R. Hill, and K Adams 1970 1 p Repr from Brit. J Radiol. (England), v. 43 p 97-99

75-00179 University Coll., Cardiff (Wales).
QUANTITATIVE RELATIONSHIPS BETWEEN ULTRASONIC CAVITATION AND EFFECTS UPON AMOEBAE AT 1 MHz
W. T. Coakley, D. Hampton, and F. Dunn (Illinois Univ., Urbana) Dec 1971 1 p Repr. from J Acoust. Soc. Amer., v. 50, pt 2, Dec 1971 p 1546-1553 Sponsored by Med Res Council

75-00180
CHROMOSOME ABERRATIONS AFTER EXPOSURE TO ULTRASOUND
W. T. Coakley, D. E. Hughes, J. S. Slade, and K. M Laurence 1971 1 p Repr. from Brit. Med J (England), 1971 p 1109-1110

75-00181
ULTRAHIGH-FREQUENCY ACOUSTIC WAVES IN LIQUIDS AND THEIR INTERACTION WITH BIOLOGICAL STRUCTURES
F. Dunn and S. A. Hawley 1965 1 p

75-00182
ULTRASONIC VISUALIZATION OF LEFT VENTRICULAR DYNAMICS
R. Eggleton, C. Townsend, J. Herrick, G. Templeton, and J. Mitchell Jul 1970 1 p Repr. from IEEE (Inst. Elec. Electron. Eng.), Trans. Sonics Ultrasonics, v. SU-17, no. 3, Jul. 1970 p 143-153

An ultrasonic system for visualizing the dynamics of the left ventricle was developed that utilizes a catheter-borne array of four transducers spaced 90 degrees apart in a plane normal to the axis of the catheter. The transducer (transceivers) are pulse sequentially at the rate of 1000/second and the data are collected over a period of about 8 seconds The cardiac cycle is arbitrarily divided into 24 equal increments or frames depicting the contour of the left ventricle at various stages during the cardiac cycle. The display phase commences upon completion of the data acquisition Compensation for the motion of the catheter within the heart and determination of the angular orientation of the catheter tip were major problems that had to be dealt with in the development of this instrumentation. The fact that data are not acquired in the same order in which they can be displayed necessitates the use of the computer for sorting and storage of echo-ranging data. The resulting views of the inner wall of the left ventricle are proving to be useful information, which should lead to a better understanding of the dynamic events of the cardiac cycle.

75-00183
ULTRASOUND: PHYSICAL, CHEMICAL AND BIOLOGICAL EFFECTS
I. E. ElPiner 1964 1 p

75-00184
EFFECT OF ULTRASOUND ON ARTERIES
John T. Fallon (Veterans Administration Hospital, Albany, N Y), William E Stehbens (Veterans Administration Hospital, Albany, N. Y), and Reginald C. Eggleton 1972 1 p Repr. from Arch. Pathol., v. 94, no 5, 1972 p 380-388

A technique for the production of ultrasonic lesions in arterial tissue was developed and the lesions so produced were investigated morphologically. Focused ultrasound (1MHz) at intensities of 25, 100, and 1500 W/sq cm was applied to the central arteries of rabbits' ears The maximum duration of exposure to these intensities was 720, 40, 1.5, and 0.1 sec, respectively The rise in temperature associated with the dosages was determined with an implanted thermocouple. The tissues were examined at 1, 30, and 72 hr after sonication. Focal lesions were found in the exposed arterial wall at intensity levels and pulse durations corresponding to threshold values of mammalian nervous tissue. The lesions in the arterial wall consisted of vacuolation, degeneration, and necrosis of smooth muscle cells in the media, loss of endothelium, and infiltration of the media with inflammatory cells

75-00185
ULTRASONIC VISUALIZATION OF ULTRASONICALLY PRODUCED LESIONS IN BRAIN
F. J Fry 1970 1 p Repr. from Confin. Neurol. (Switzerland), v. 32, 1970 p 38-52

Three anatomically discrete ultrasonically produced brain lesions in the rhesus monkey was visualized ultrasonically in the immediate post-lesion period, as well as three weeks later. After sacrifice at three weeks, the histologically prepared brain sections

in the lesion area were compared with the chogram information to verify lesion placement and size. The correlation data indicate that ultrasonic visualization means can be used to aid in the accurate placement of brain lesions. Additionally, the lesions can hopefully be controlled in size and shape by this means. Subsequent examination of the lesions over a long period of time also appears to be possible with ultrasonic visualization techniques.

75-00186
ULTRASOUND FOR VISUALIZATION AND MODIFICATION OF BRAIN TISSUE
F J Fry, R F Heimburger, L V Gibbons, and R C Eggleton Jul 1970 1 p Repr from IEEE (Inst. Elec. Electron Eng). Trans Sonics Ultrasonics, v SU-17, no 3, Jul 1970 p 165-169

Techniques for the detailed, in vivo visualization and modification of internal brain structures via ultrasonic means were developed and studied in animals and man. The instrumentation used in these studies included high-gain large-aperture ceramic transducers positioned in space by a specially adapted Cincinnati turret drill. The system provides for the use of either simple, compound, or omnidirectional scanning modes. When the brain is viewed through an acoustically transparent window, essentially all soft-tissue fluid-filled space interfaces can be visualized, and in some instances gray-white matter interfaces can be seen clearly. Brain lesions produced by high-intensity focused ultrasound are tissue specific and can be spaced in vivo to conform with the complex geometry of a given brain structure. These ultrasonic lesions, as well as those produced by mechanical or electrolytic methods, can be visualized ultrasonically immediately after their placement.

75-00187
THRESHOLD ULTRASONIC DOSAGES FOR STRUCTURAL CHANGES IN THE MAMMALIAN BRAIN
F J Fry, G Kossoff, R Eggleton, and F Dunn Dec 1970 1 p Repr from J Acoust Soc Amer, v 48, no 6, Dec 1970 p 1413-1417

The relationship between the acoustic intensity and the time duration of exposure, for a single pulse, necessary to produce a threshold lesion in the cat brain was studied. Focused ultrasound of 1, 3, and 4 MHz was employed with intensities ranging from 100 to 20,000 W/sq cm with the corresponding pulse duration from 7 to 0.0002 sec, respectively. Three types of lesions were observed attending three regions. At the lower intensities and long time durations of exposure, the lesion is produced by a thermal mechanism. At the highest intensities and shortest time durations, cavitation is believed to be the mechanism which is responsible for the sometimes randomly appearing lesions. At intermediate dosages the lesions are formed by a mechanical mechanism which is thus far not well understood. These results exhibit good agreement with that of other investigators on both the cat and rat brain.

75-00188
ECHOCARDIOGRAPHY OF THE AORTIC ROOT
Raymond Gramiak and Pravin M Shah Oct 1968 1 p Repr. from Invest Radiol, v 3, no. 5, Sep.-Oct. 1968 p 356

The echo pattern of the aortic root is elicited by locating the typical echo of the mitral valve and then angulating the transducer medially and cephalically. The characteristic echo pattern of the aortic root consists of paired undulating signals three to five cm apart. These signals move anteriorly during systole and posteriorly during diastole. Their position is central in relation to echoes arising from the mitral and tricuspid valves corresponding to the anatomic position of the aortic root. The movement pattern is identical to the mitral annulus, which also represents a portion of the fibrous skeleton of the heart. Lesser echoes originating between the undulating margins of the aortic root were identified as arising from the valve cusps by correlating their motion with the production of the cardiac sounds. Further support was gained by recording abnormally intense and distorted signals in patients with calcific aortic stenosis. Anatomic validation of the aortic origin of these echoes was obtained by means of ultrasonic contrast injections made during radiologic studies of the aortic root. Saline was injected in the supravalvular position during continuous echocardiographic recording and was detected as a cloud of echoes limited by the parallel signals of the aortic root. Systolic movement of the aortic cusps was accompanied by the delivery of noncontrast blood from the left ventricle which produced defects in the contrast image paralleling the excursion of the linear signals from the cusps.

75-00189 National Inst of Mental Health, Bethesda, Md.
ULTRASOUND IN DIAGNOSTIC MEDICINE. A REPORT FROM THE RADIATION STUDY SECTION OF THE NATIONAL INSTITUTES OF HEALTH
E C Gregg, F L Thurstone, and E R Epp Dec. 1973 1 p Repr from Eng. Radiol., v 109, Dec. 1973 p 737-742

75-00190
ACOUSTIC INTENSITY MEASUREMENTS ON ULTRASONIC DIAGNOSTIC DEVICES
C R Hill 1971 1 p Repr from Ultrasonographia Medica (Vienna), v 2 p 21-27

75-00191
CELL DISRUPTION BY ULTRASOUND
D E Hughes and W L Nyborg 1962 1 p Repr from Science, v 138 p 108-114

75-00192
EFFECTS OF AIRBORNE ULTRASOUND ON MAN
J J Knight 1968 1 p Repr from Ultrasonics (England), v 6 p 39-41

75-00193
CONDITION OF SOME ENZYME SYSTEMS OF HEART AND BRAIN ENERGY METABOLISM IN RABBITS UNDER THE EFFECT OF ULTRASOUND
E P Kutuzova 1972 1 p Repr. from Vop. Kurortol., Fizioter. Lech Fiz. Kult (USSR), v. 36, no. 5, 1971 p 428-431

In the early period of development of experimental atherosclerosis in rabbit heart and brain tissue (after 40 days), activity of the enzymes of glycolysis and the pentose and tricarboxylic acid cycles decreased, indicating an inhibition of energy metabolism. A series of ultrasonic treatments at an intensity of 0.6 and 1 W/sq cm had no appreciable effect on these enzymes in tissues of normal animals. Ultrasound at an intensity of 0.6 W/sq cm applied to animals with experimental atherosclerosis increased the activity of succinate dehydrogenase in heart tissue and aldolase in brain tissue, indicating a stimulatory effect of this dose on metabolism. A dose of 1 W/sq cm was less effective in influencing the enzyme systems of carbohydrate metabolism in these animals.

75-00194
SELECTIVE HEATING EFFECTS OF ULTRASOUND IN HUMAN BEINGS
J. F Lehmann, B. J DeLateur, and D. R Silverman 1966 1 p Repr from Arch. Phys. Med. Rehabil., v. 47 p 331-339

75-00195
RATE OF PULSE WAVE PROPAGATION IN ULTRASONIC TREATMENT OF PATIENTS WITH DEFORMING ARTHROSIS WITH CONCOMITANT DISEASES OF THE CARDIOVASCULAR SYSTEM
N. V. Mikhailova 1972 1 p Repr. from Vop Kurortol., Fizioter. Lech. Fiz. Kult. (USSR), v. 36, no 5, 1971 p 426-428

Patients (110) were treated with continuous or intermittent ultrasonic waves of an intensity of .2-.8 W/sq cm and phonophoresis with hydrocortisone. Considerable improvement resulted in 18.2% of cases, improvement in 75.4% and no change in 6.4%. Pulse curves in the carotid and femoral arteries were measured to determine changes in rate of pulse wave propagation, reflecting degree of elasticity of vessel walls, as a result of treatment. Rates are generally found to be elevated in

arteriosclerosis and hypertensive disease A decrease in rate occurred in all cases It was especially marked in older patients (60-74 yr old) given continuous ultrasonic treatment, where the rate dropped from 10 10-8 67 m/sec These figures indicated the beneficial effect of ultrasonic treatment on cardiovascular disease

75-00196
ULTRASONICS IN MEDICINE: REVIEW
J A Newell 1963 1 p Repr from Phys Med Biol (England), v 8 no 3, 1963 p 241

The physical aspects of ultrasound are briefly discussed, and relevant formulae and constants used in the generation and propagation of sound energy in various human and animal tissues are given Methods of measurement and some possible hazards are mentioned, but the main emphasis is on diagnostic and surgical application of ultrasound Treatment of Meniere's and Parkinson's diseases by high-intensity ultrasound are discussed and low-intensity applications in brain, heart and eye are singled out for detailed description Although controlled application of ultrasound is relatively new, all the evidence seems to prove its great value in medicine, and the author concludes with suggestions about its future development

75-00197
ULTRASONICS IN MEDICINE
J A Newell Dec 1967 1 p Repr from Electron Power (England), v 13, Dec 1967 p 449-451

The scientific and technological tools of industry often find application in medicine, ultrasonics is no exception It is used at high intensities for the treatment of certain conditions, and at intermediate intensities for physiotherapy treatment At low intensities it has a range of uses, all similar to the industrial application of nondestructive testing, all are essentially diagnostic applications

75-00198 Nagasaki Univ (Japan)
EXPERIMENTAL STUDY ON ULTRASONIC ATTENUATION IN THE BRAIN
Hidenobu Oshibuchi 1972 1 p Repr from Acta Med Nagasaki (Japan), v 15, no 1-4, 1971 p 26-48

An experimental study was made in rabbits to determine participating factors and the method of participation in ultrasonic attenuation changes in the brain Bilateral ligation of the jugular veins, auto-rebreathing of exhaled gas, blockage of carotid blood flow and physiological salt solution injection upon puncture of the posterior cistern were the methods used The relation of brain H_2O content, cerebral blood flow and CSF (cerebral spinal fluid) pressure changes with ultrasonic attenuation change was studied Either decrease or CSF pressure increase participated with ultrasonic attenuation increased Either brain H2O content increase, cerebral blood flow increase or CSF pressure decrease participated when ultrasonic attenuation decreased

75-00199
EFFECT OF HIGH-FREQUENCY NOISE ON MAN
R Reinhold, K Rasche and W Werner Jul 1972 1 p Repr from Z Gesamte Hyg (West Germany), v 18 Jul 1972 p 485 488

75-00200 Massachusetts Inst of Tech, Cambridge
AN ANALYSIS OF LESION DEVELOPMENT IN THE BRAIN AND IN PLASTICS BY HIGH-INTENSITY FOCUSED ULTRASOUND AT LOW MEGAHERTZ
T C Robinson and P P Lele 1972 1 p Repr from J Acoust Soc Amer, v 51, 4 pt 2, 1972 p 1333-1351

Thermal factors are believed to play a dominant role in the development of the structural and functional effects of irradiation of the nervous system with focused ultrasound at low-MHz frequencies Similar mechanisms are postulated to underline the effects of irradiation in methacrylate, frequently used as a test material This study was undertaken to determine if thermal mechanisms alone can explain the development of trackless focal alterations (lesions) and all of their measurable characteristics in plastic as well as in brain A purely thermal model is assumed and analytical prediction of lesion development and lesion size and shape for varying values of ultrasonic and thermal constants and controllable variables (frequency, focusing, dosage, target depth, etc.) is attempted. An empirical equation to describe the axial and radial ultrasonic energy distribution at the focus in water is derived. Appropriate heat transfer equations are developed for temperature distributions resulting from ultrasonic irradiation. The computed temperature profiles are plotted against nondimensionalized parameters. Temperatures at the lesion boundary were determined experimentally. Lesion dimensions read off the computed temperature profiles at the measured lesion boundary temperature are compared with experimental data. Within the range of ultrasonic parameters used in this study, the development of lesions in the brain are explained by thermal mechanisms A cat brain was used.

75-00201
ANIMAL TOXICITY STUDIES WITH ULTRASOUND AT DIAGNOSTIC POWER LEVELS
M G Smyth 1966 1 p

75-00202
CONCISE PHYSICS OF ULTRASOUND AS APPLIED IN OPHTHALMOLOGY
A Sokollu 1969 1 p Repr from Int Ophthalmol. Clin, v 9, 1969 p 793-828

75-00203
ACOUSTICAL IMAGING OF BIOLOGICAL TISSUE
F L Thurstone Jul 1970 1 p Repr. from IEEE (Inst Elec Electron. Eng). Trans Sonics Ultrasonics, v. Su-17, no 3, Jul 1970 p 154-157

In any imaging system the subjective quality and in turn the usefulness of the system is dependent upon the information detection, processing, and display procedures that are employed. Numerous techniques have been investigated over a period of years for the purpose of imaging biological tissue structures using ultrasound as the investigating radiant energy. However, the clinical and research applicability of these techniques has not become widespread because of the limited diagnostic usefulness of the images Several image factors that influence the diagnostic usefulness of ultrasound images are discussed.

75-00204 Naval Medical Research Inst., Bethesda, Md.
ULTRASOUND DOSAGE FOR EXPERIMENTAL USE ON HUMAN BEINGS
W D Ulrich Aug. 1971 1 p
(AD-731075, NAVMED-M4306 01-1010BXK9-2)

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15. Abstract

This Lecture Series No.78 on the subject of Radiation Hazards, is sponsored by the Aerospace Medical Panel of AGARD, and is implemented by the Consultant and Exchange Programme.

During the last 25 years there has been a remarkable development and increase in the number of processes and devices that utilise or emit non-ionizing radiation which includes ultra-violet, visible light, infrared, microwave, radiofrequency, ultrasound. Such devices are used in all sectors of our society for military and industrial, telecommunications, medical and consumer applications. Although there is information on biological effects and potential hazards to man from exposure to these energies, considerable confusion and misinformation has permeated not only the public press but also some scientific and technical publications. Much of the confusion stems from misunderstanding of the fundamentals of energy-tissue interaction, threshold phenomena, personnel exposure and product emission standards, such as those promulgated in the United States and adopted by the Western Countries and Japan in contrast to the personnel exposure criteria of Eastern European Countries. This series of Lectures by experts in the field provides a scientifically accurate, authoritative review and critical analysis of the available information and concepts to give a basis for informed judgements and judicious application of these energies for maximal benefit and minimum risk or hazard to man.